Searching for New Colored States at the Early LHC

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ATLAS Jamboree
Brookhaven National Lab
January 10, 2011

with Daniele Alves & Eder Izaguirre

arXiv:1003.3886, 1008:0407, 1101:xxxx

Outline

Simplified Models

Jets + MET Simplified Models

First LHC Results and Their Implication

Going Forward to $1 fb^{-1}$

LHC is the New Energy Frontier

(but you still need luminosity)

The first Jets+MET Search came out with 70 nb^{-1} of integrated luminosity

ATLAS NOTE

ATLAS-CONF-2010-065

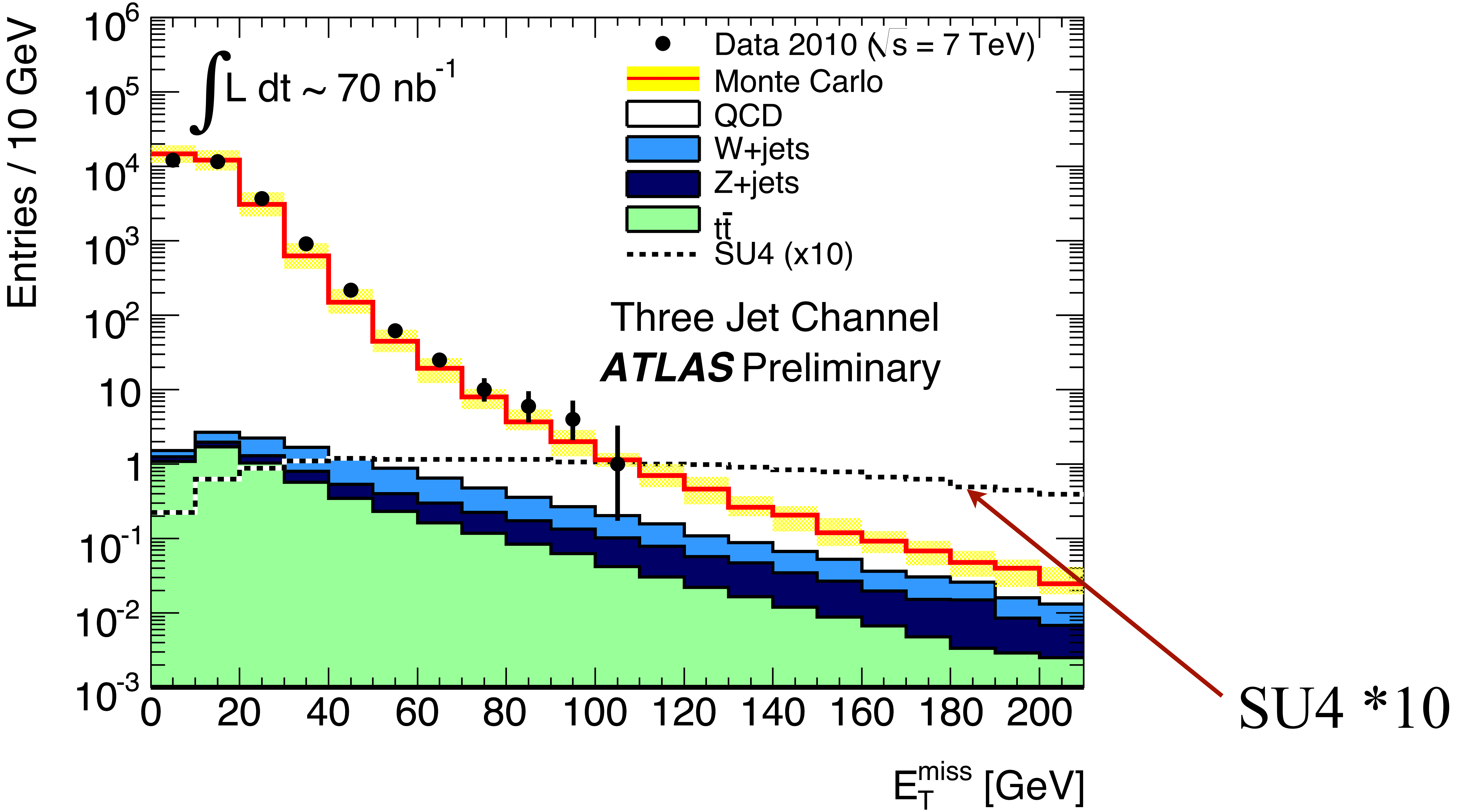
20 July, 2010

Early supersymmetry searches in channels with jets and missing transverse momentum with the ATLAS detector

Abstract

This note describes a first set of measurements of supersymmetry-sensitive variables in the final states with jets, missing transverse momentum and no leptons from the $\sqrt{s} = 7$ TeV proton-proton collisions at the LHC. The data were collected during the period March 2010 to July 2010 and correspond to a total integrated luminosity of $70 \pm 8\,\mathrm{nb}^{-1}$. We find agreement between data and Monte Carlo simulations indicating that the Standard Model backgrounds to searches for new physics in these channels are under control.

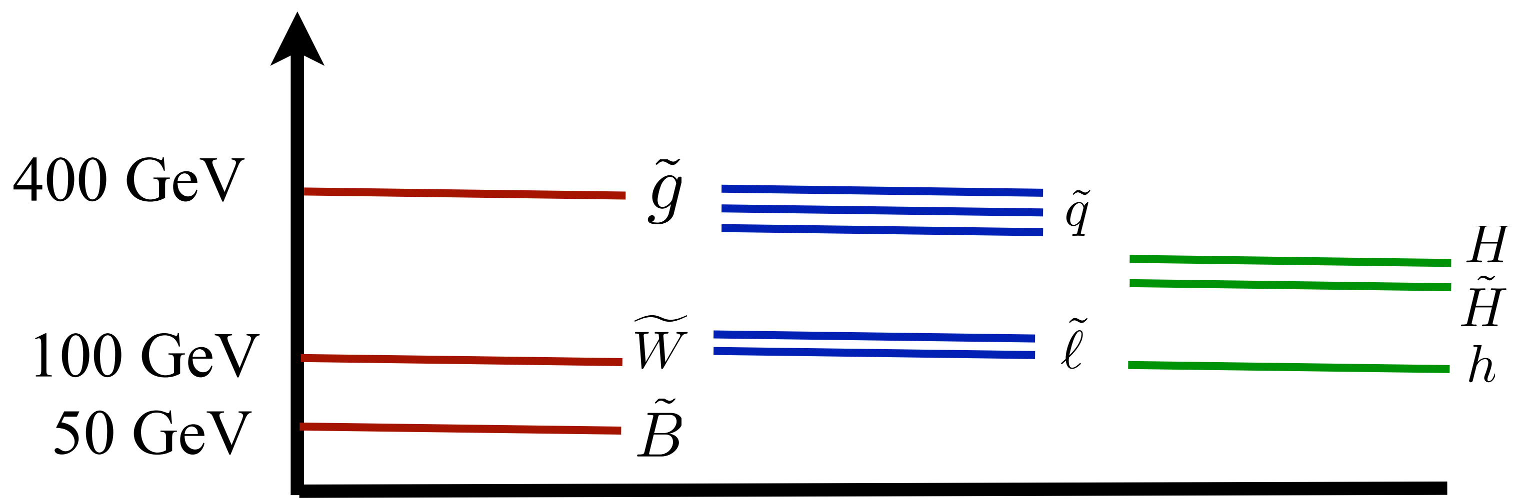
Amazing that such an early search is possible!



SU4*10

As light as possible inside of mSugra

Still had to multiply it by 10 to be visible



But with $70 nb^{-1}$, what should we expect?

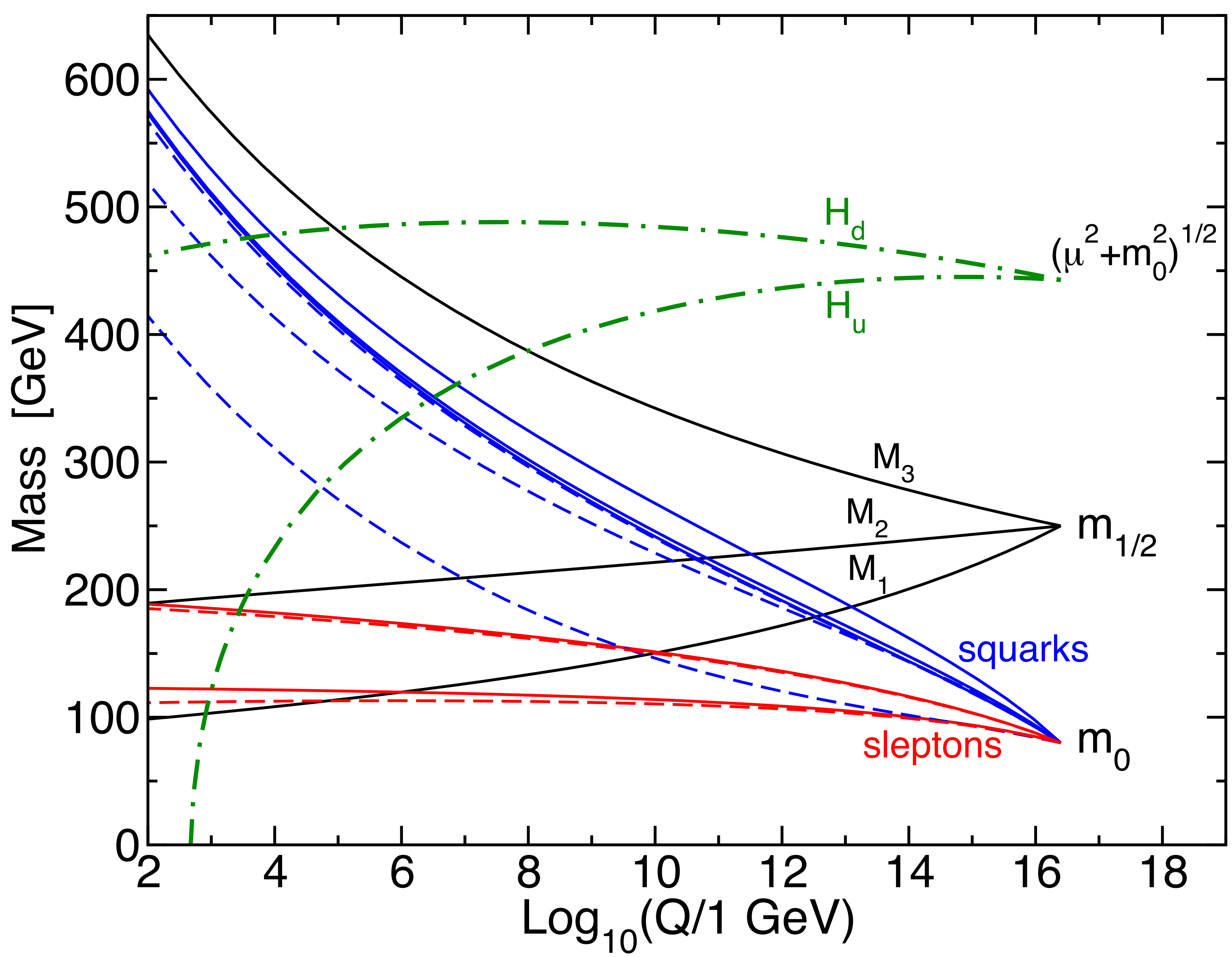
No other theories were explored

mSugra Review

5 Parameters at the GUT Scale

$$m_{\frac{1}{2}}, m_0^2, A_0, B_\mu, \mu$$

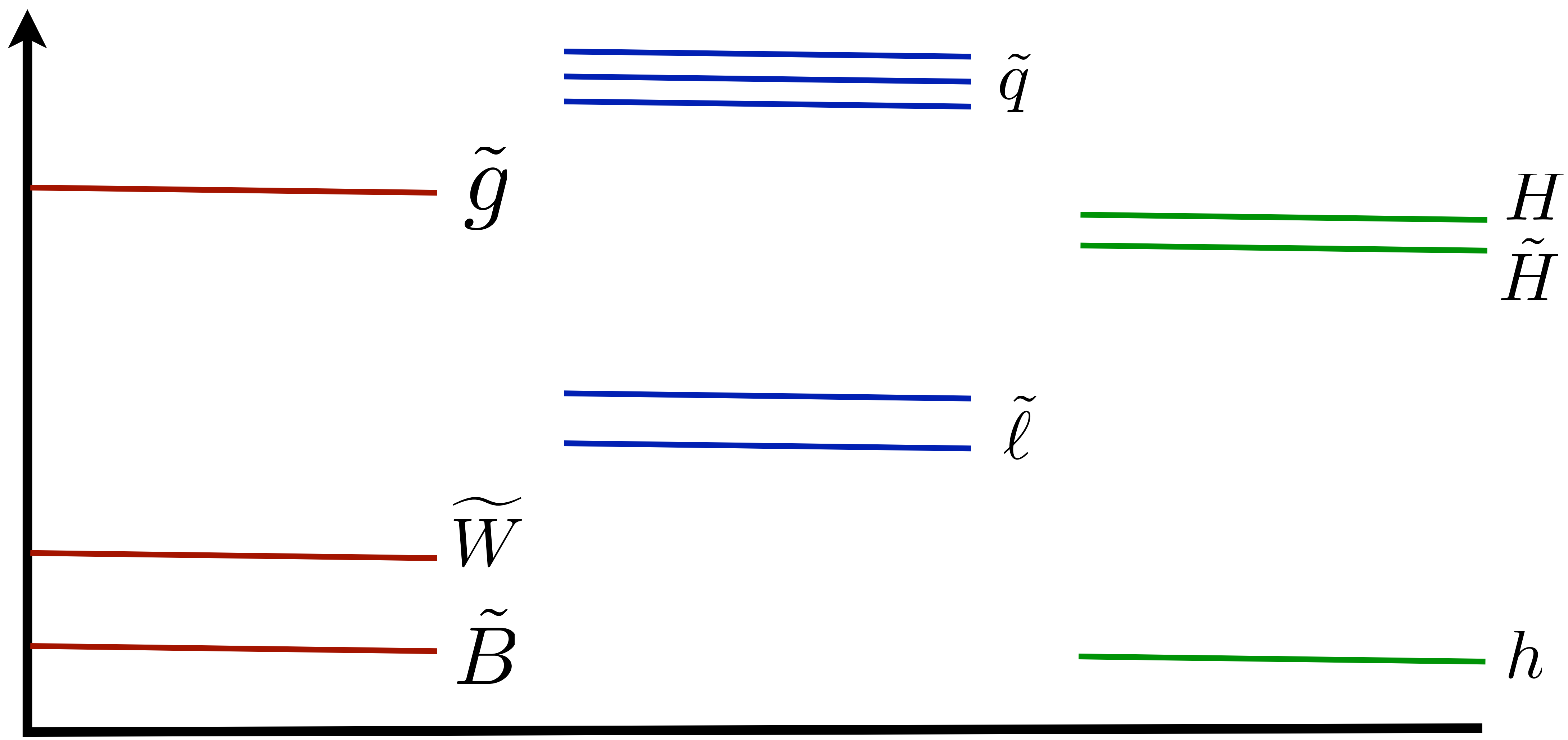
$$B_\mu, \mu \rightarrow v_{\mathrm{EW}} = 246\ \mathrm{GeV}, \tan\beta$$



mSugra and "Gaugino Mass Unification"

$$m_{\tilde{g}} : m_{\tilde{W}} : m_{\tilde{B}} = \alpha_3 : \alpha_2 : \alpha_1 \simeq 6 : 2 : 1$$

Most models look like this



A shocking lack of diversity

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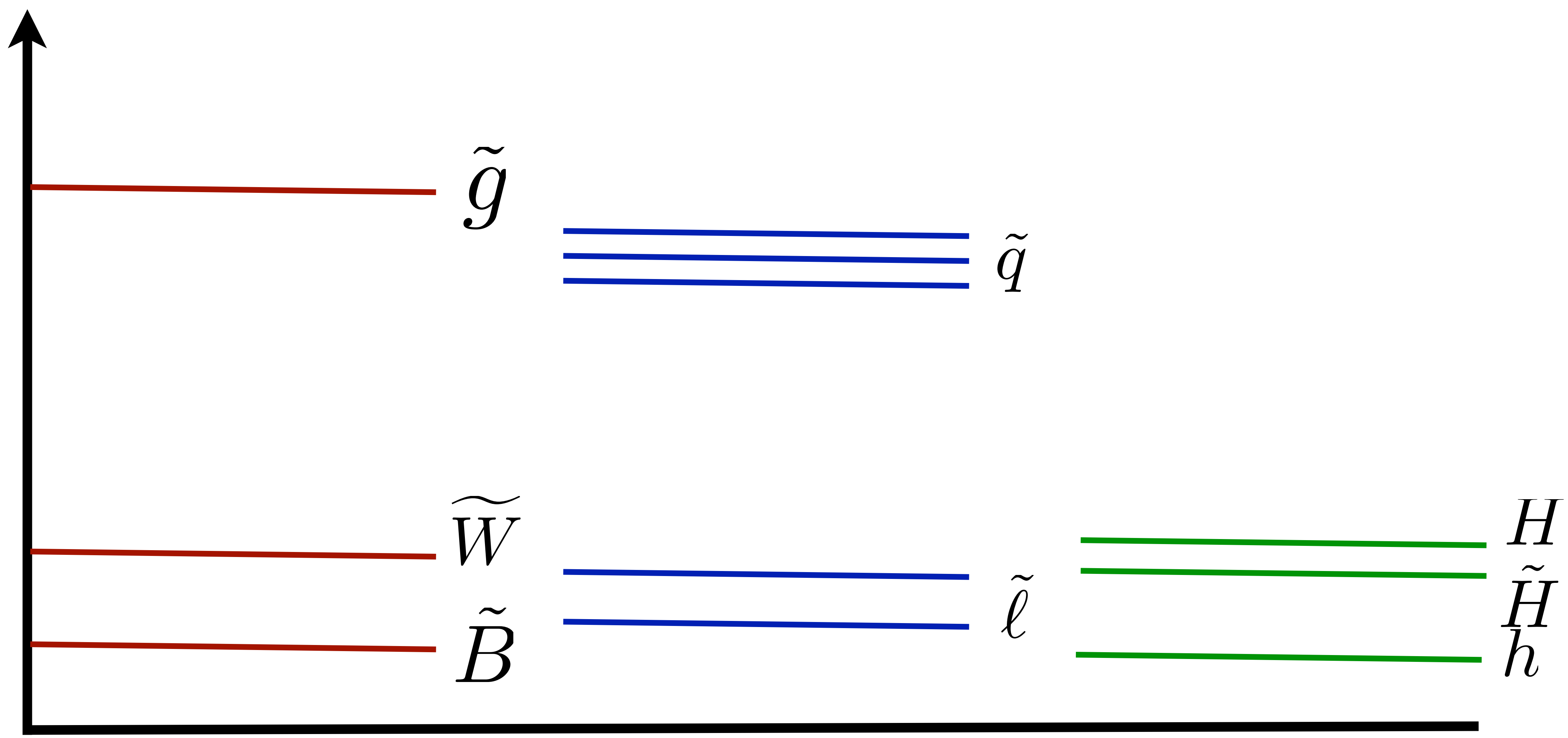


A shocking lack of diversity

The Phenomenological MSSM

$$m^2_{\tilde{q}}, m^2_{\tilde{u}^c}, m^2_{\tilde{d}^c}, m^2_{\tilde{\ell}}, m^2_{\tilde{e}^c}$$

5 for 1st 2 Generations

5 for 3rd Generations

$$m_{\tilde{g}}, m_{\tilde{W}}, m_{\tilde{B}}, \mu$$

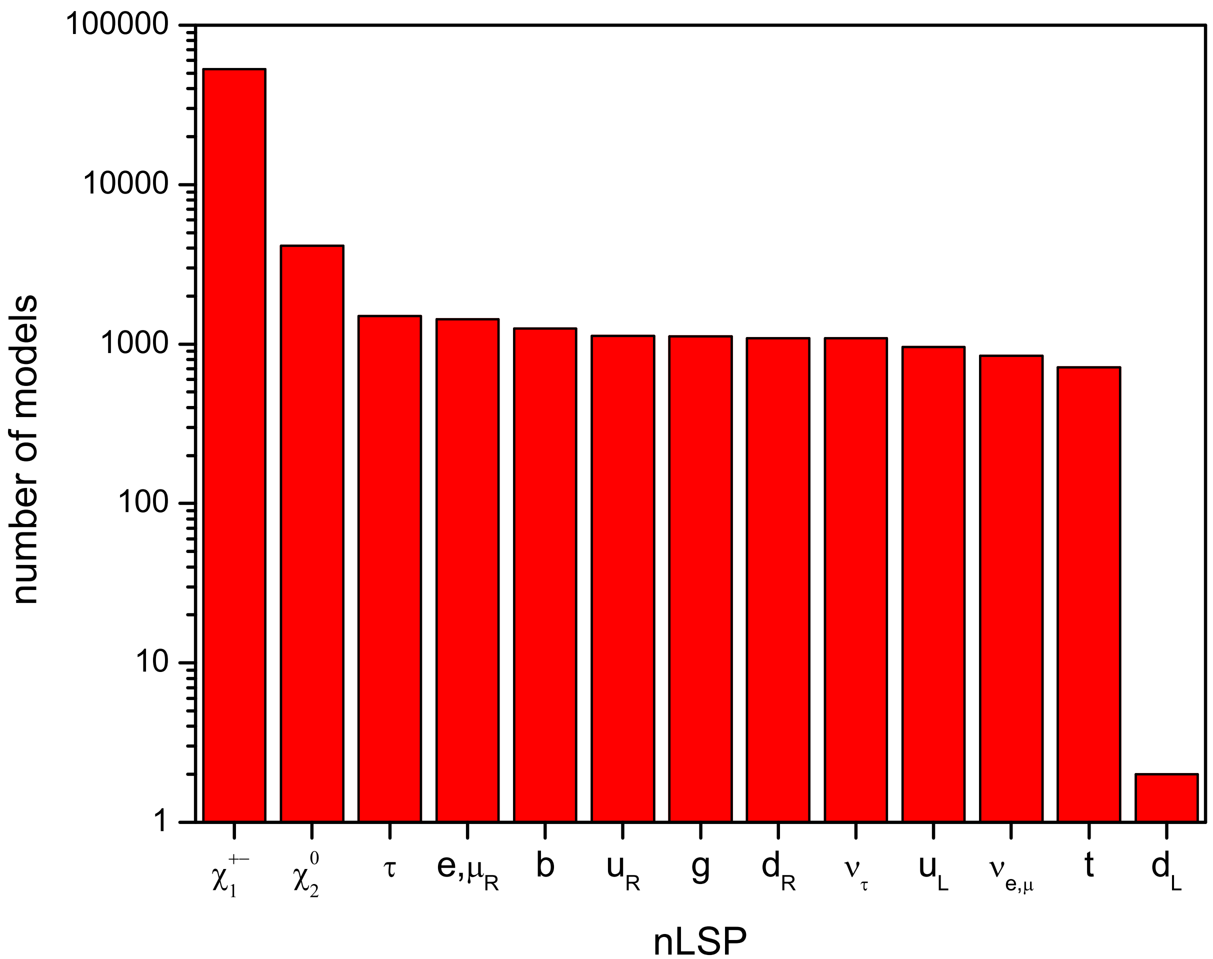
4 for *-ino masses

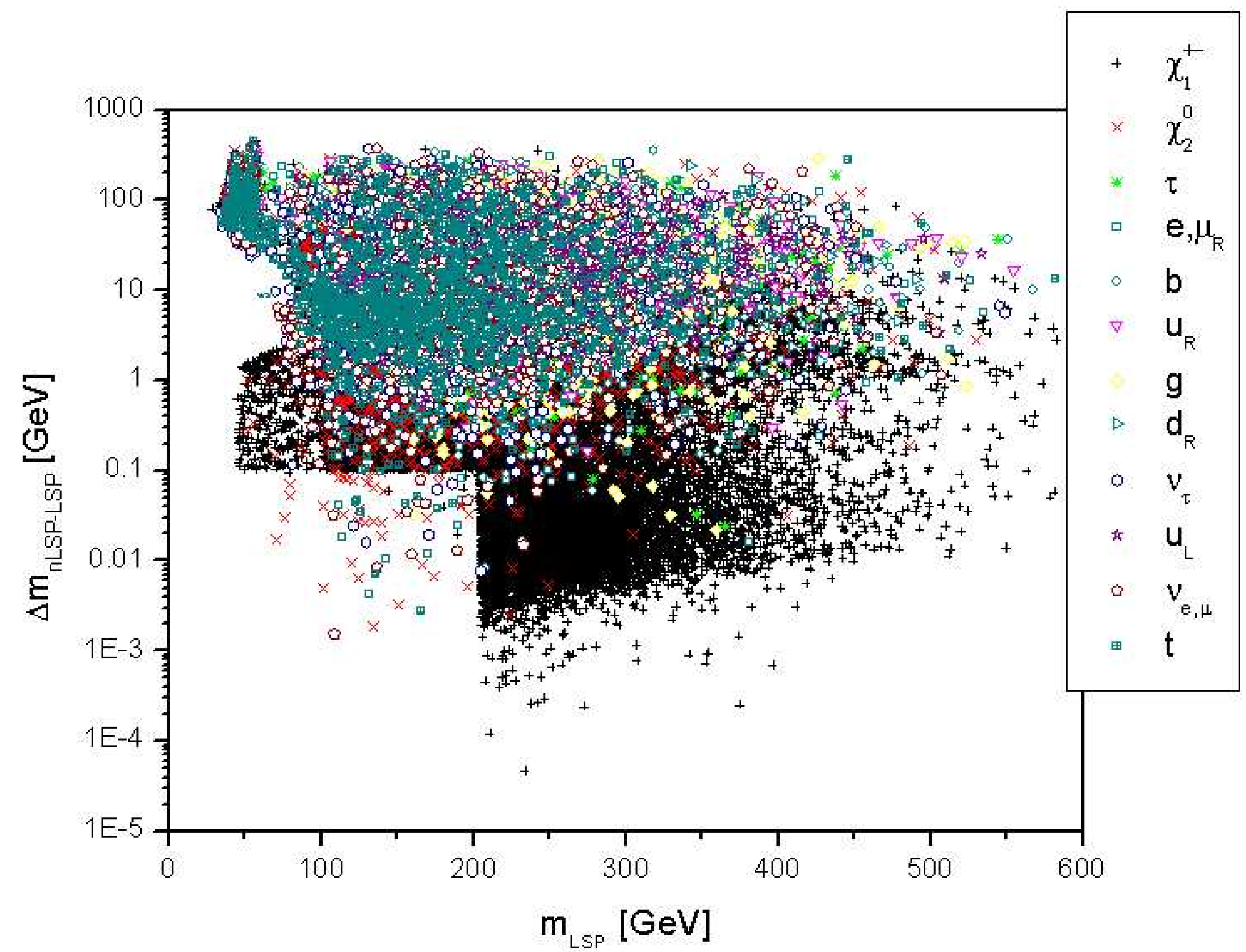
$$A_t, A_b, A_\tau$$

3 for A-terms

$$m^2_{h_u}, m^2_{h_d}, B_\mu$$

3-1 for Higgs Sector





Berger, Gainer, Hewett, Rizzo 2008

How to parameterize this without using a CPU-Century?

Need to cover signature space better

Real models have dozens of parameters

Sometimes small/reasonable perturbations
can make huge differences in the visibility of a model

Need to simplify and abstract models

Simplified Models

(Effective Field Theories for Collider Physics)

Limits of specific theories

Only keep particles and couplings relevant for searches

Still a full Lagrangian description

Removes superfluous model parameters

Masses, Cross Sections, Branching Ratios (*e.g.* MARMOSET)

Add in relevant modification to models (*e.g.* singlets)

Not fully model independent, but greatly reduce model dependence

Captures specific models

Including ones that aren't explicitly proposed

Easy to notice & explore kinematic limits

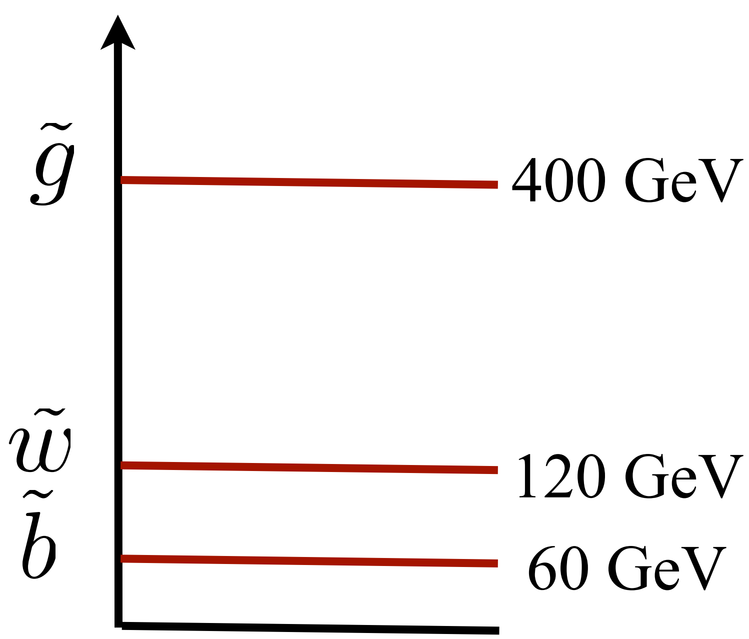
Hides Similarities Between Theories

Color octet that decay into missing energy

MSSM

High Cut-Off

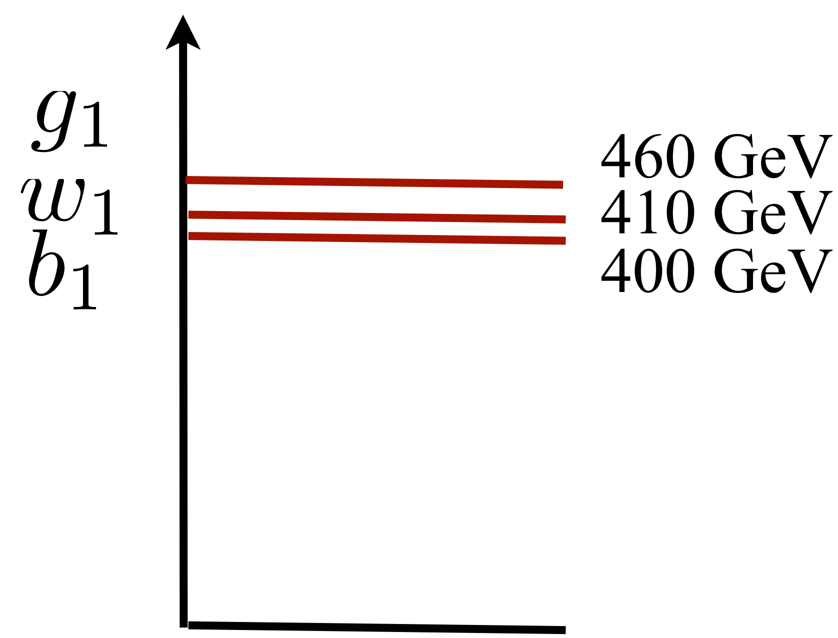
Large Mass Splittings



Universal Extra Dimensions

Low Cut-Off

Small Mass Splittings



Similar in spirit, radically different in practice

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Simplified Models

Jets + MET Simplified Models

First LHC Results and Their Implication

Going Forward to $1 fb^{-1}$

Jets + MET

Solution to Hierarchy Problem

If the symmetry commutes with $SU(3)_C$,
new colored top partners

note twin Higgs exception: $SU(3)_{C_1} \times SU(3)_{C_2} \ltimes \mathbb{Z}_2$

Dark Matter

Wimp Miracle: DM a thermal relic if
mass is 100 GeV to 1 TeV

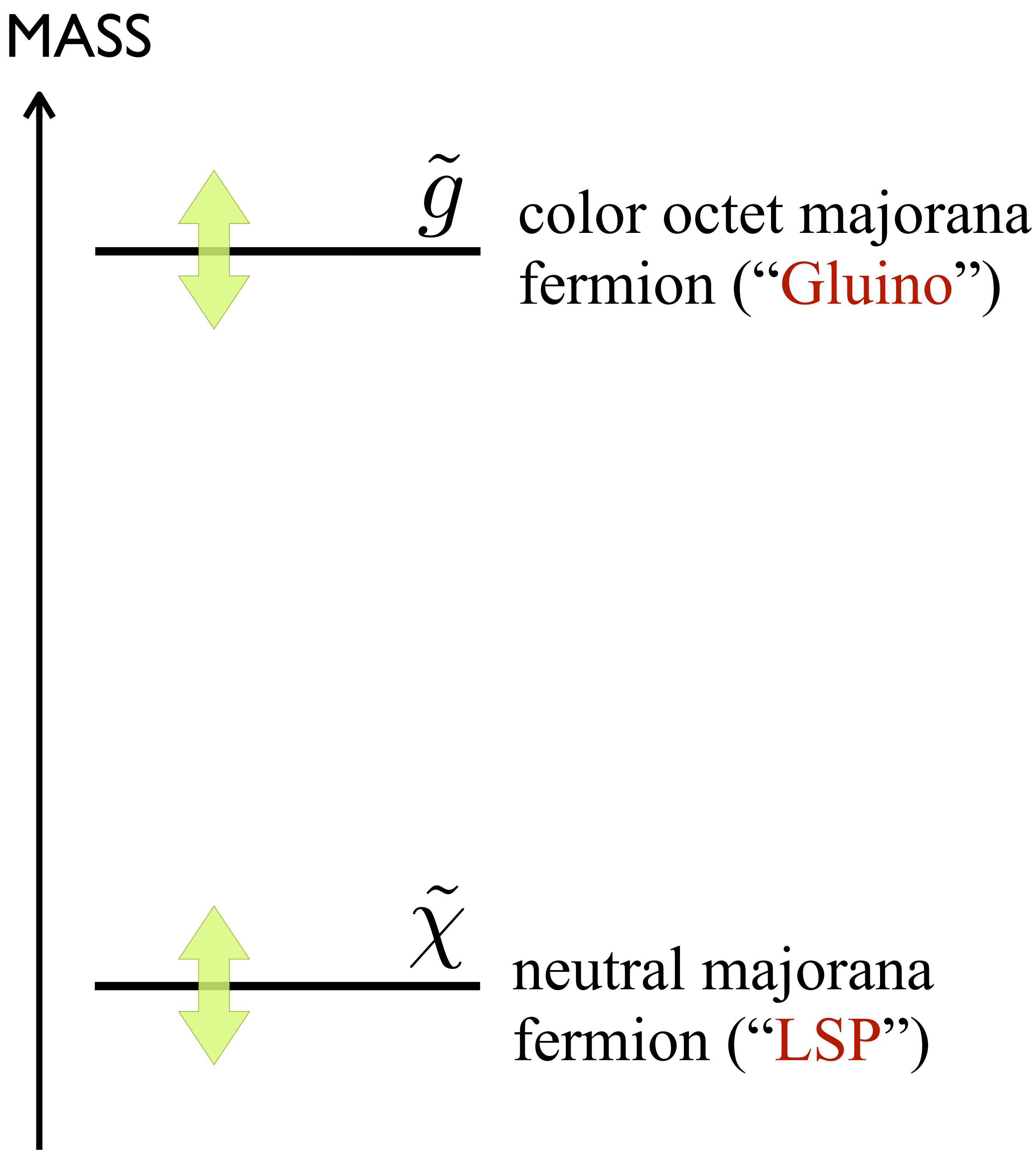
Usually requires a dark sector,
frequently contains new colored particles
(e.g. Split Susy)

Fewest requirements on spectroscopy

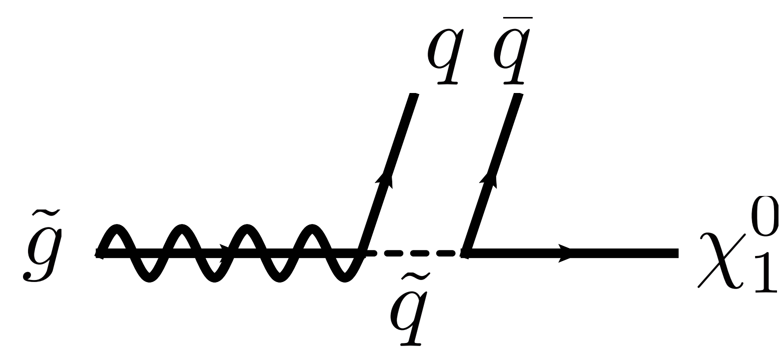
Doesn’t require squeezing in additional states to decay chains

Simplified Models

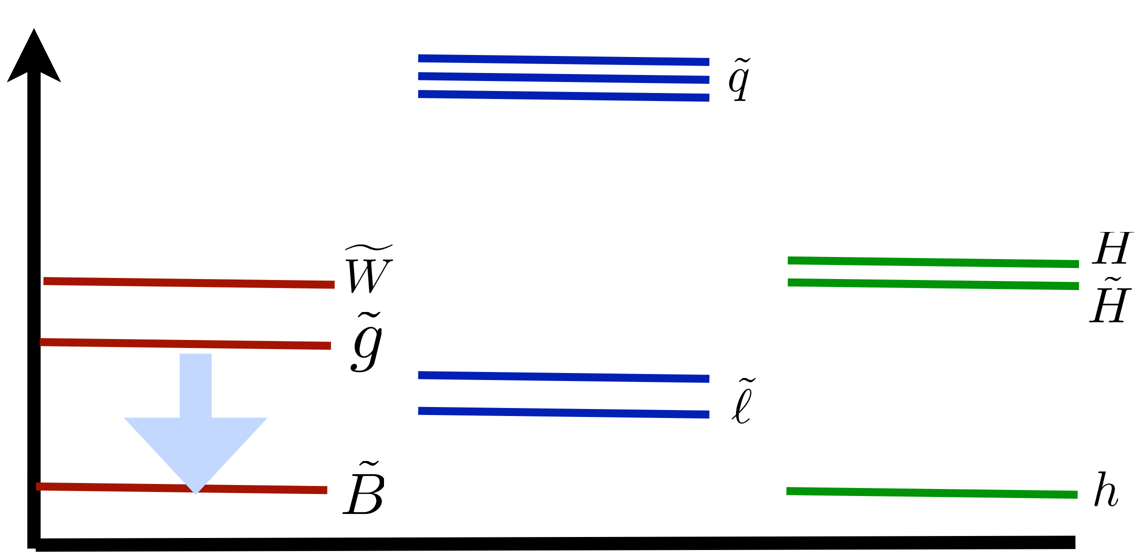
Direct Decays



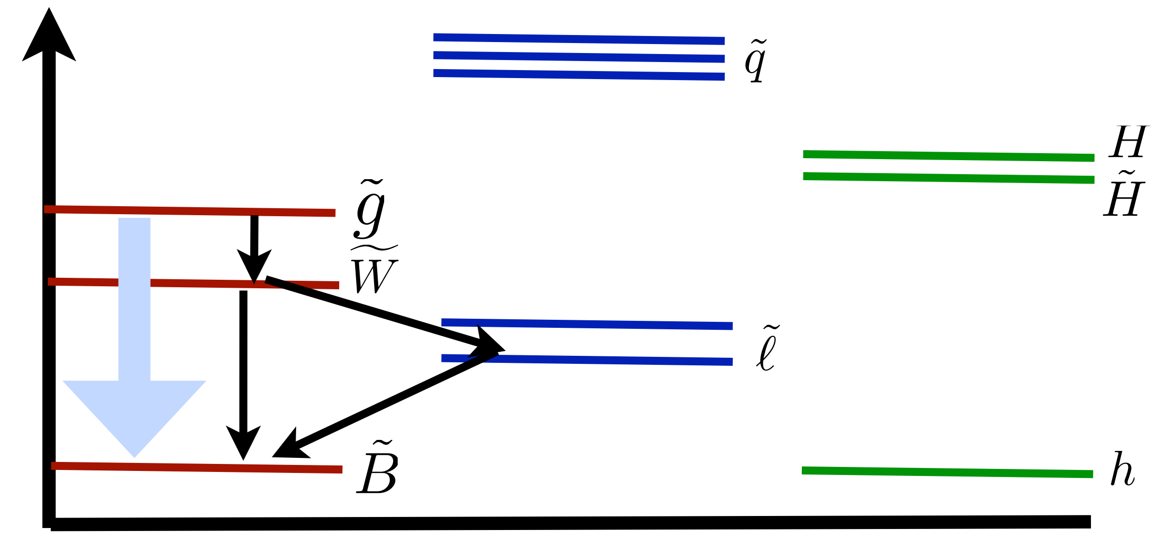
THREE-BODY



Directly Decaying Gluino

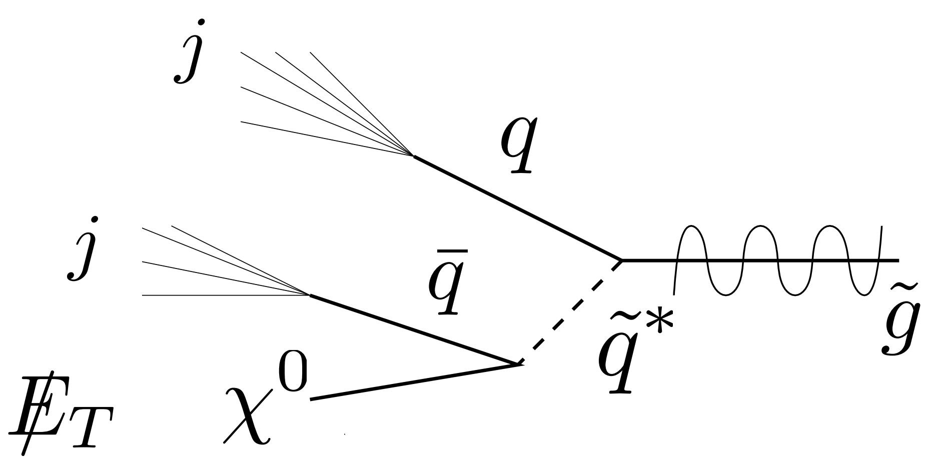


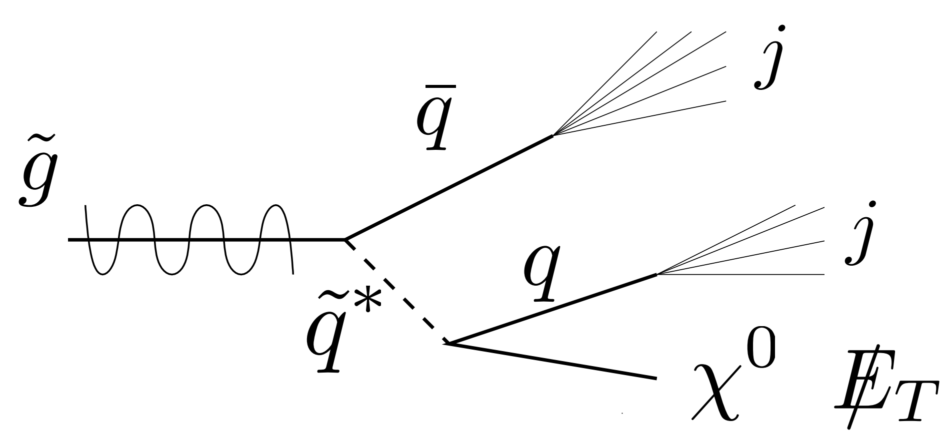
$\mathrm{Br} = 100\%$



$\mathrm{Br} \sim 10\%$

Study one decay mode $\tilde{g} \longrightarrow q\bar{q}\tilde{\chi}^0$

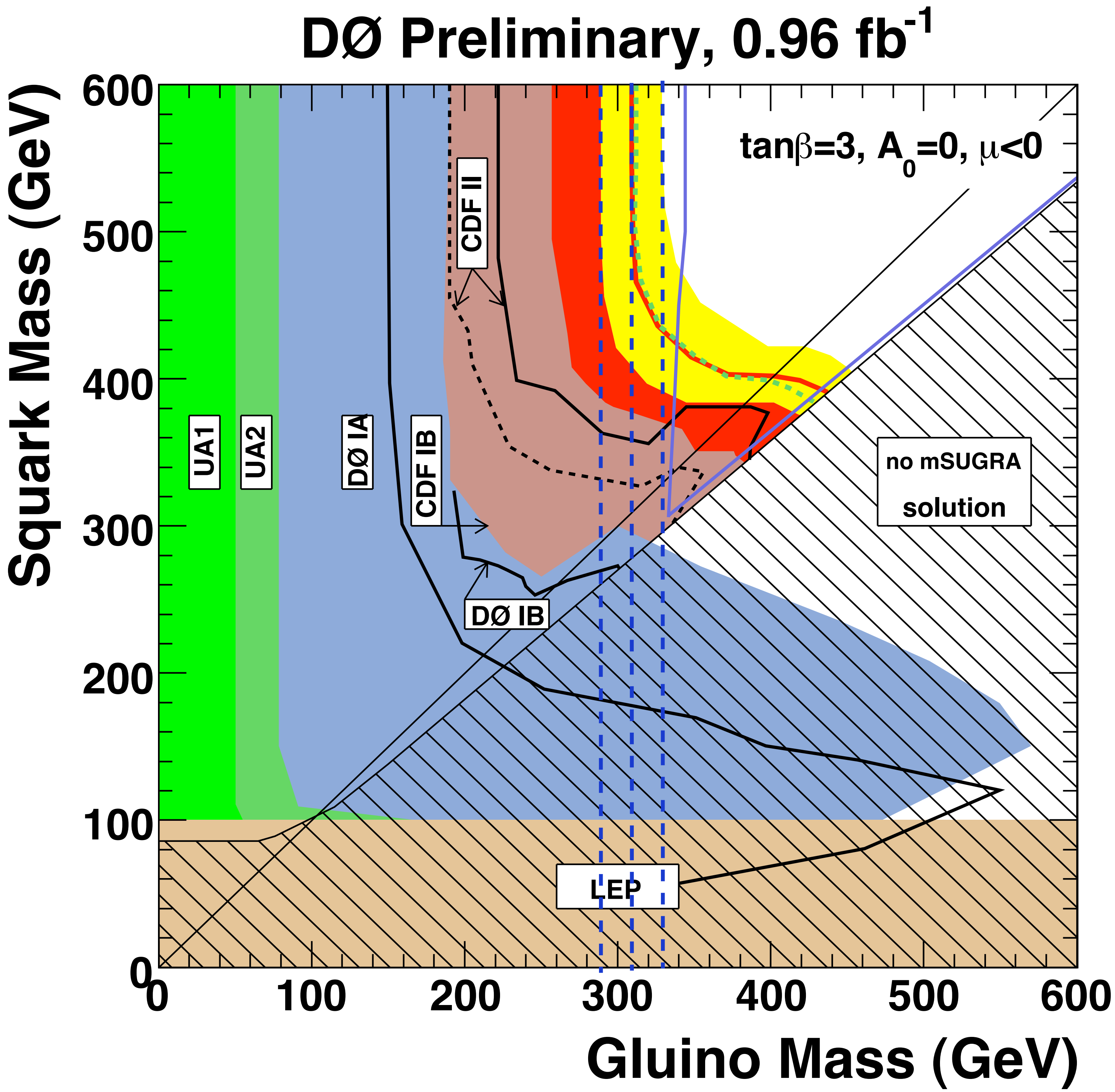




Keep masses and total cross section free

$$m_{\tilde{g}} \qquad m_{\chi^0} \qquad \sigma(pp \longrightarrow \tilde{g}\tilde{g}X)$$

What are the current limits?



Hard to interpret...

Model Independent Constraints

Electrically Neutral Colored Particles

Weak model independent limits

Limits come from event shape variables at LEP
(*e.g.* Thrust)

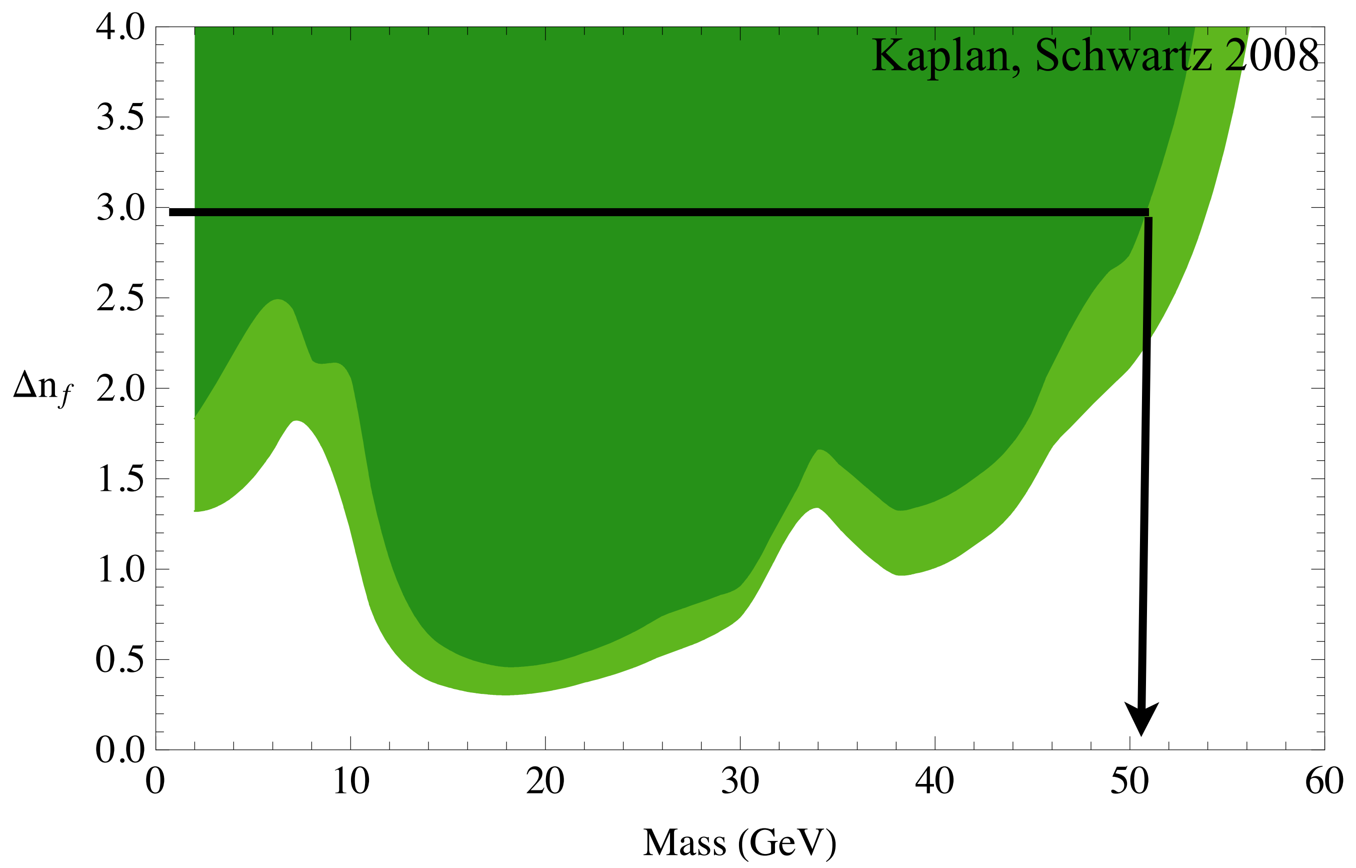
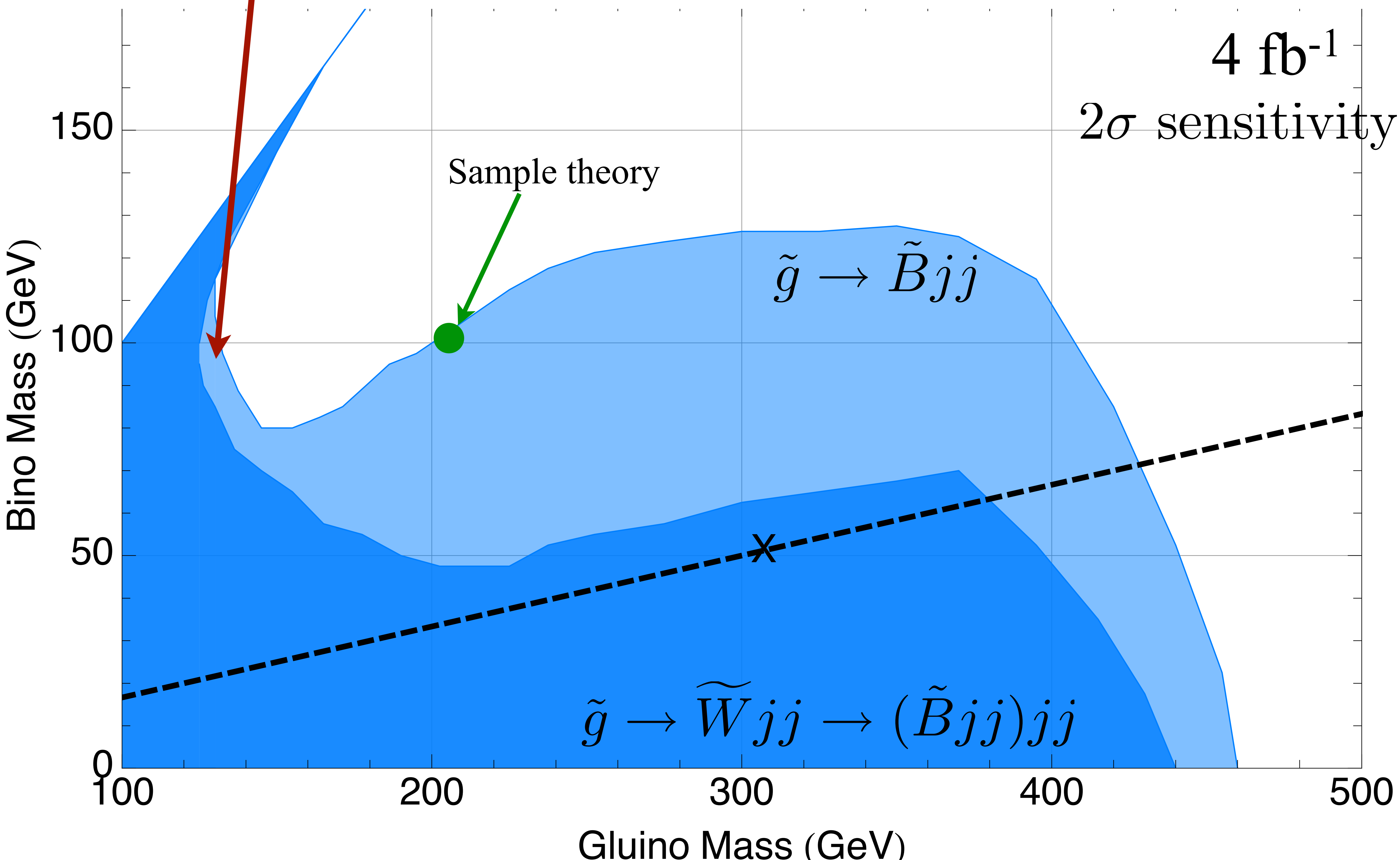


FIG. 2: Bounds on light colored particles from LEP data. The darker region is completely excluded at 95% confidence. The lighter region is an uncertainty band including estimates of various theoretical uncertainties.

Tevatron Reach

$m_{\tilde{g}} \gtrsim 120\ \mathrm{GeV}$

A 50 GeV gluino *is* “ruled out”!

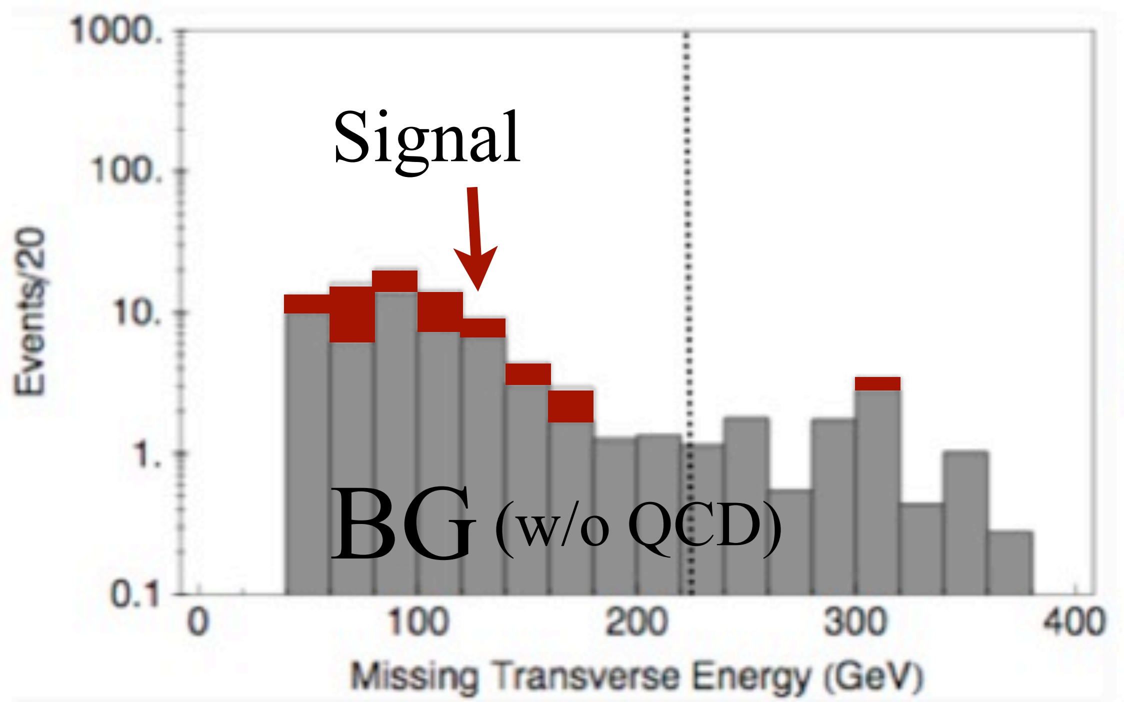


Alwall, Le, Lisanti, Wacker 2008

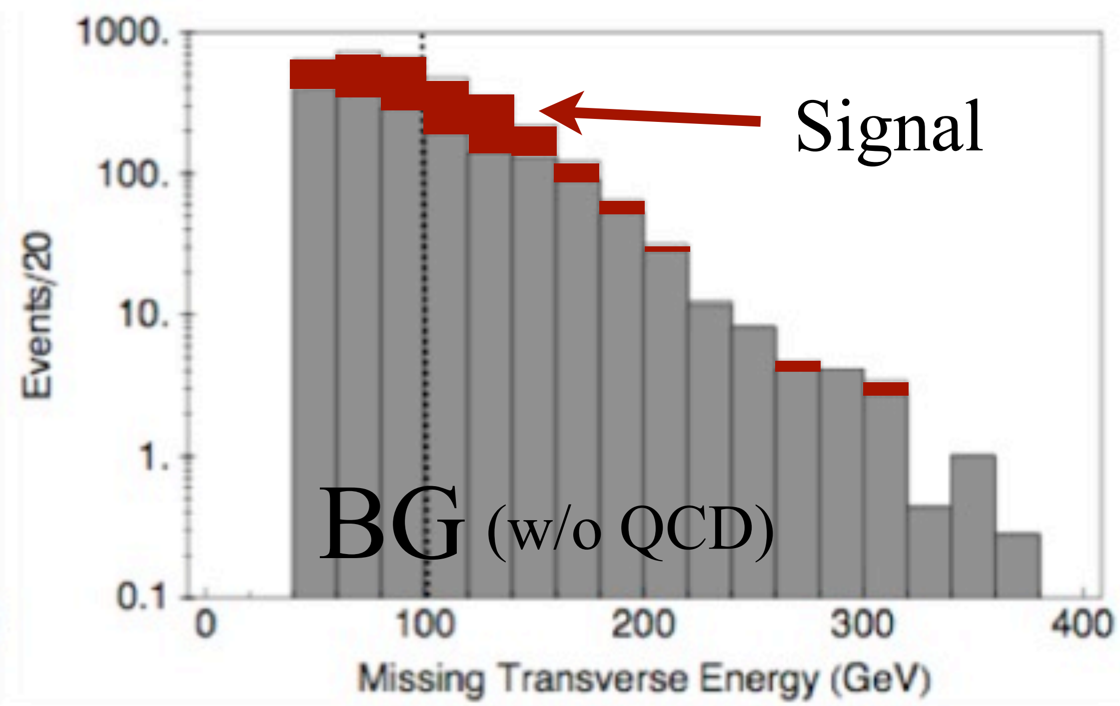
These were "best case scenario numbers"

$$e.g. \quad m_{\tilde{g}} = 210 \text{ GeV} \quad m_{\tilde{B}} = 100 \text{ GeV}$$

Assumed no missed discoveries



$H_T \geq 300$ GeV $\quad \not{E}_T \geq 225$ GeV



$H_T \geq 150$ GeV $\quad \not{E}_T \geq 100$ GeV

Alwall, Le, Lisanti, Wacker 2008

Tevatron never searched in physics parameter space

Possibility for light gluinos lurking

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Estimates of ATLAS ICHEP Reach

Can 70nb^{-1} improve Tevatron results?

Set limit on $\sigma(pp \to \tilde{g}\tilde{g}X)\,\epsilon$

Cut	Topology	$1j + \not{E}_T$	$2^+j + \not{E}_T$	$3^+j + \not{E}_T$	$4^+j + \not{E}_T$
1	p_{T1}	$> 70\,\mathrm{GeV}$	$> 70\,\mathrm{GeV}$	$> 70\,\mathrm{GeV}$	$> 70\,\mathrm{GeV}$
2	p_{Tn}	$\leq 30\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}(n=2)$	$> 30\,\mathrm{GeV}(n=2,3)$	$> 30\,\mathrm{GeV}(n=2-4)$
3	$\not{E}_{T\,\mathrm{EM}}$	$> 40\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$
4	$p_{T\,\ell}$	$\leq 10\,\mathrm{GeV}$	$\leq 10\,\mathrm{GeV}$	$\leq 10\,\mathrm{GeV}$	$\leq 10\,\mathrm{GeV}$
5	$\Delta\phi(j_n, \not{E}_{T\,\mathrm{EM}})$	none	$[>0.2, >0.2]$	$[>0.2, >0.2, >0.2]$	$[>0.2, >0.2, >0.2, \mathrm{none}]$
6	$\not{E}_{T\,\mathrm{EM}}/M_{\mathrm{eff}}$	none	> 0.3	> 0.25	> 0.2
	N_{Pred}	46^{+22}_{-14}	6.6 ± 3.0	1.9 ± 0.9	1.0 ± 0.6
	N_{Obs}	73	4	0	1
	$\sigma(pp \to \tilde{g}\tilde{g}X)\epsilon\vert_{95\%\ \mathrm{C.L.}}$	663 pb	46.4 pb	20.0 pb	56.9 pb

$3^+j + \not{E}_T$ usually most effective

Need to calculate efficiencies

(the hard part)

We need to know what fraction of
the events from a given theory pass the cuts

Madgraph $\longrightarrow$ Pythia $\longrightarrow$ PGS $\longrightarrow$ Cuts

$pp \to \tilde{g}\tilde{g} + \leq 2j$ $\quad$ $\tilde{g} \to 2j\, \chi_1^0$

(MLM matched)

Efficiency is the fraction of events that passed the cuts

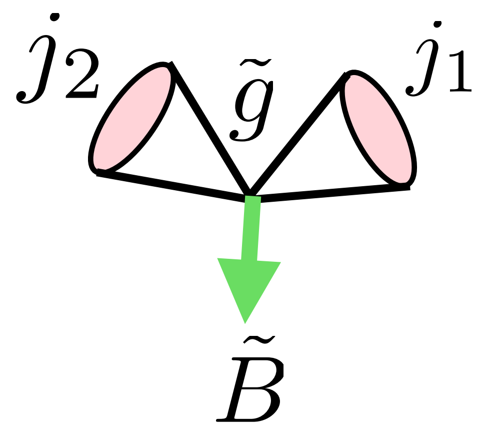
Do this for each $(m_{\tilde{g}}, m_{\chi})$ pair

Validated PGS to about 15% accuracy

A look at how PS/ME matching alters the signal

150 GeV particle going to 140 GeV LSP and 2 jets

In rest frame of each gluino:
two 5 GeV “jets” and a LSP with 3 GeV momentum



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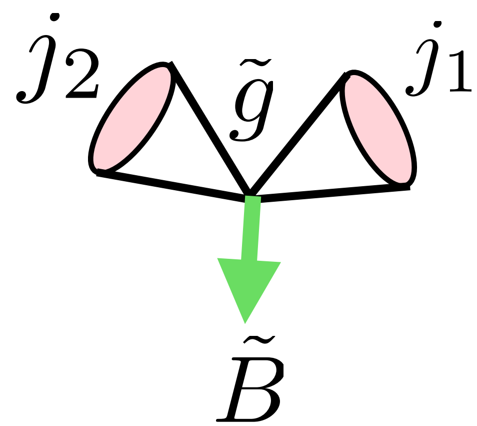
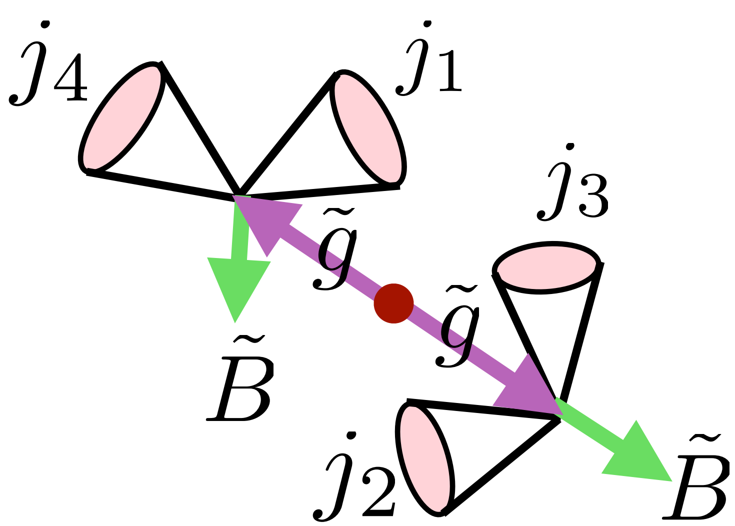
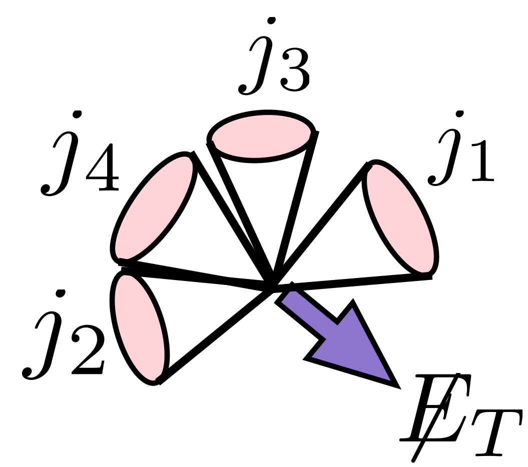


Parton level



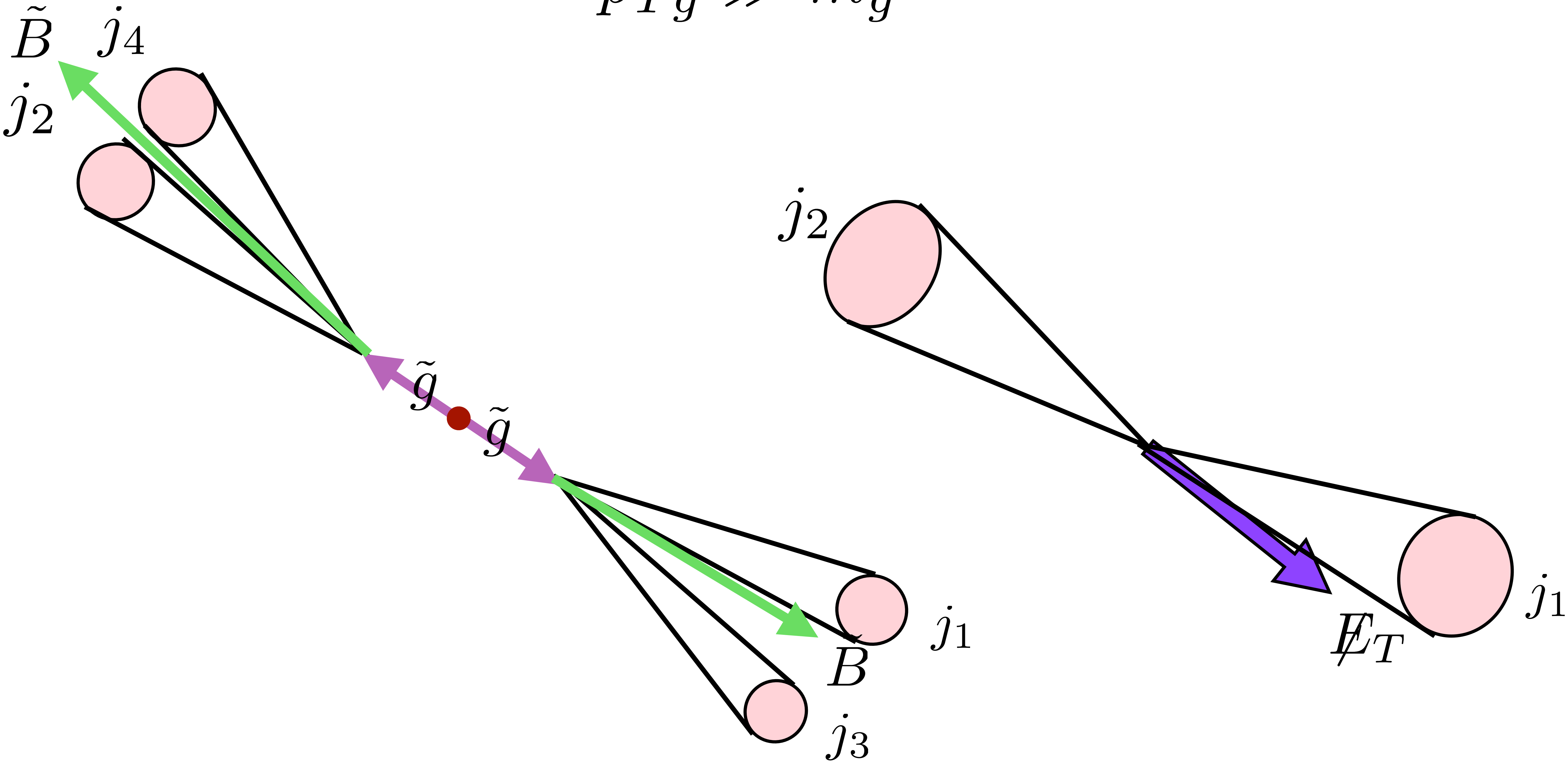
Detector level



Totally invisible: faked by QCD with $\sqrt{\hat{s}_{\mathrm{BG}}} \sim 20$ GeV

Give the gluino big boost!

$$p_{T\tilde{g}} \gg m_{\tilde{g}}$$

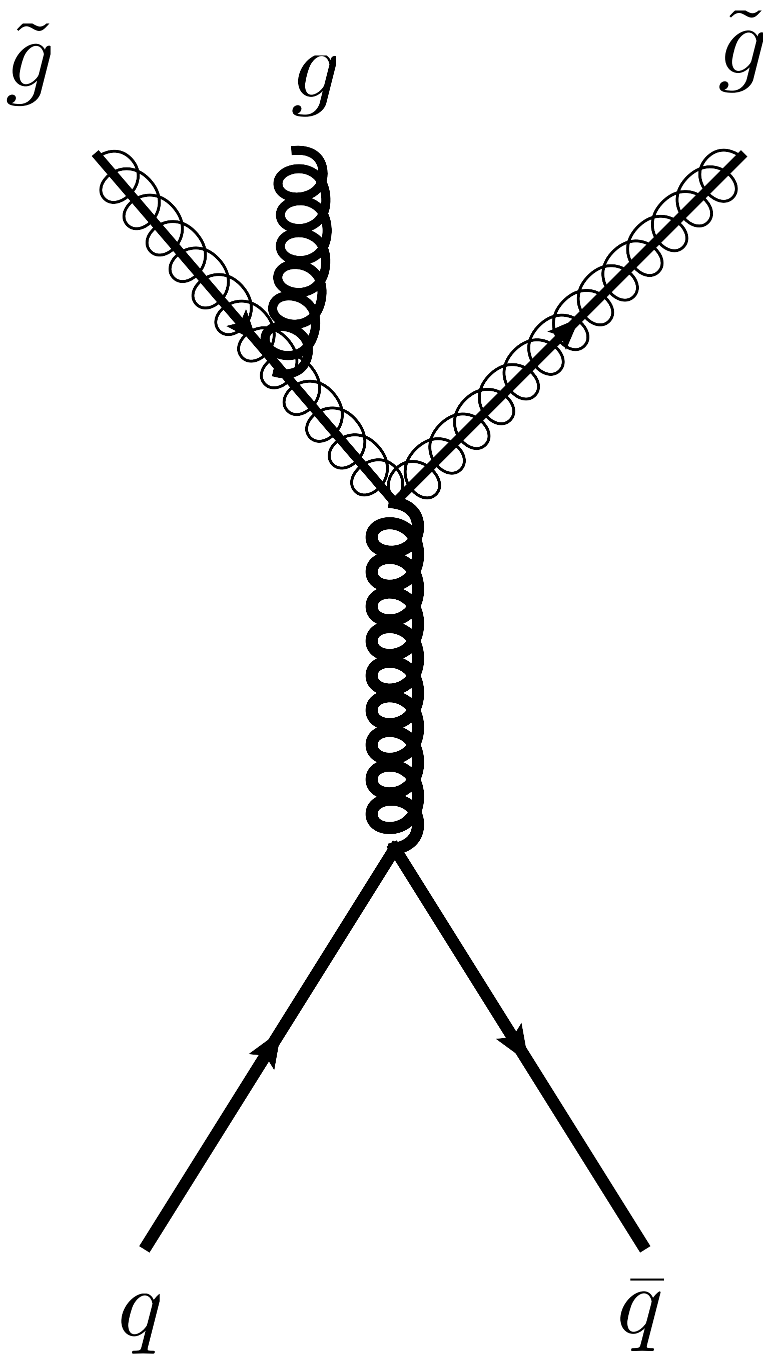


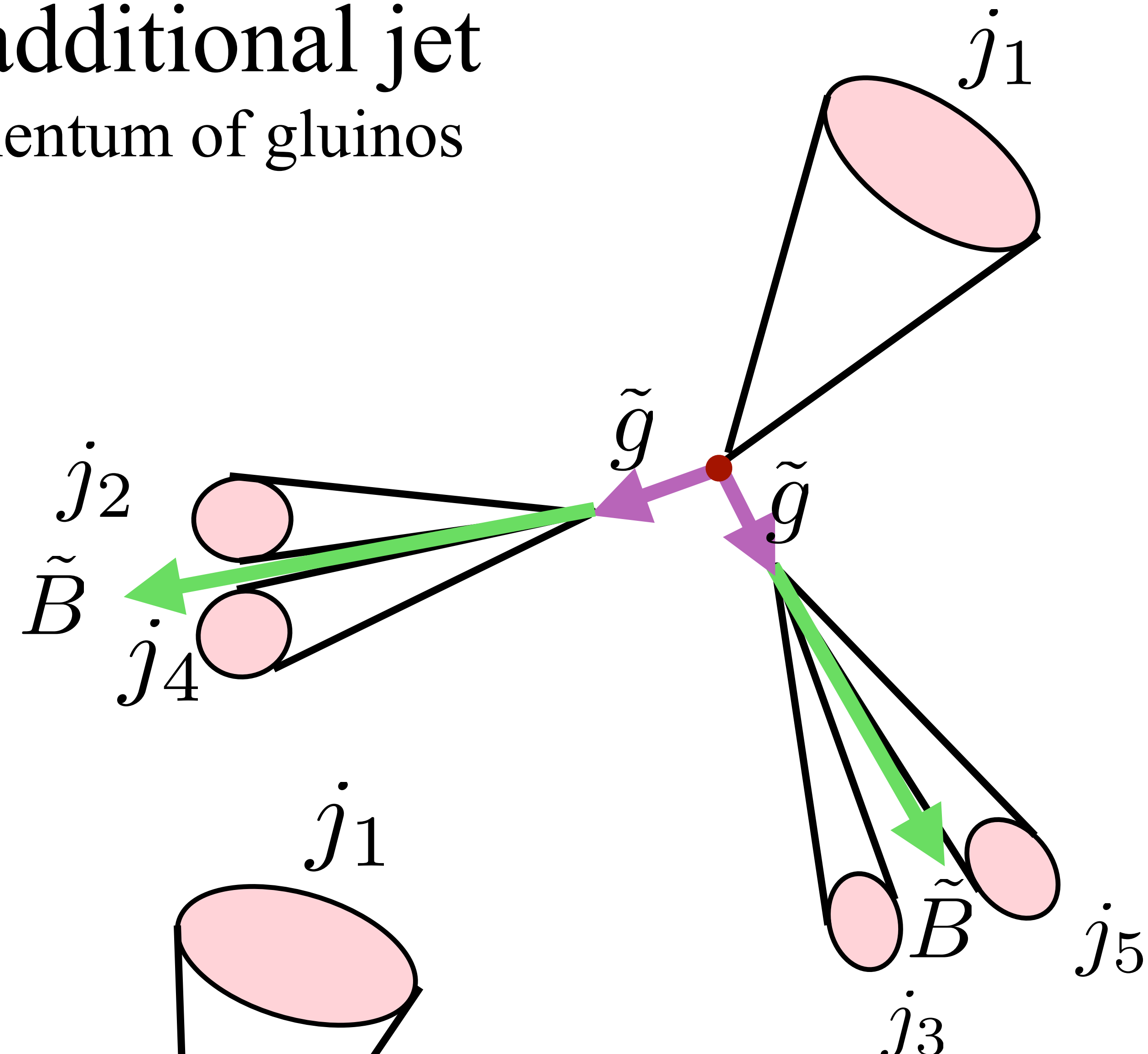
Jets merge and MET points in direction of jet

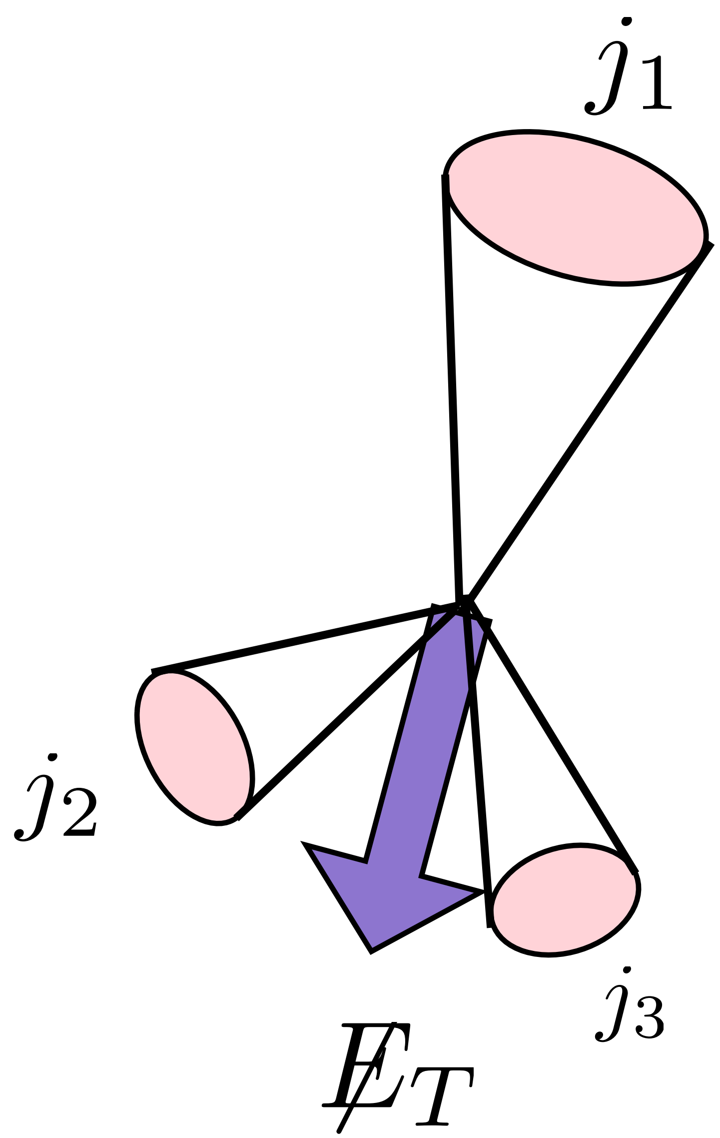
More energy, but looks like jet mismeasurement

Radiate off additional jet

Unbalances momentum of gluinos



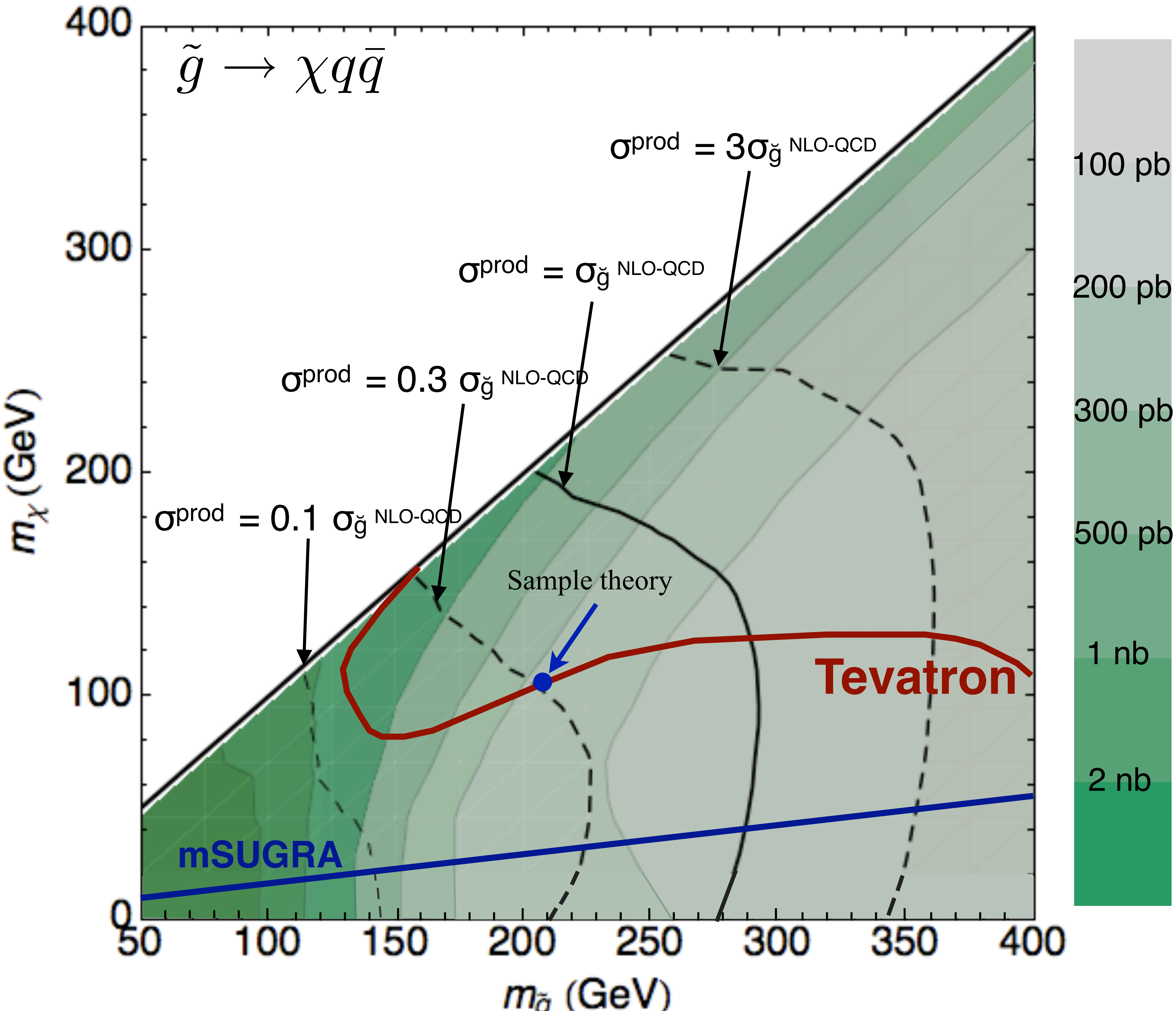




Need to calculate the spectrum of radiation reliably

Putting it all together

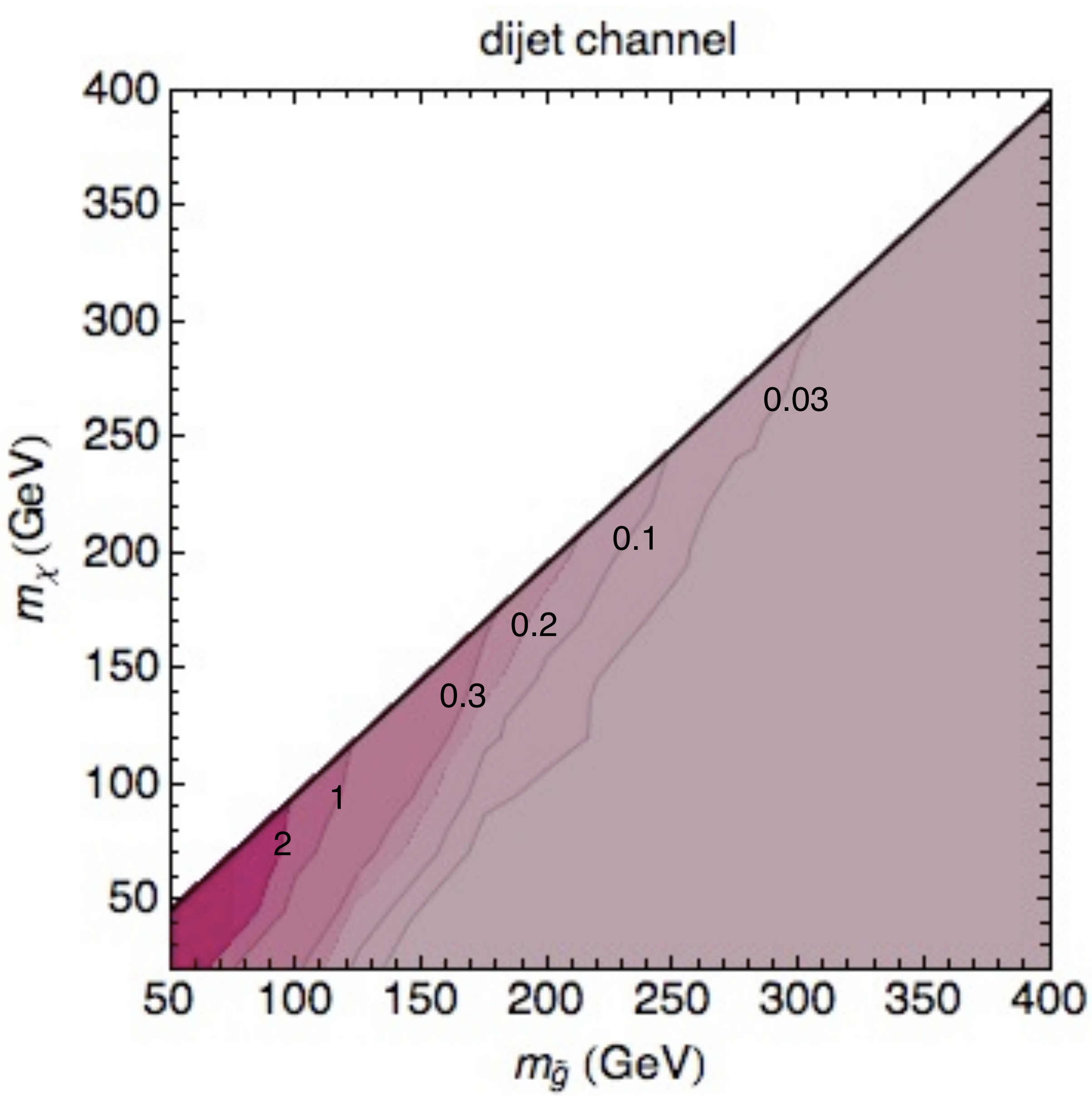
There could have been discoveries!

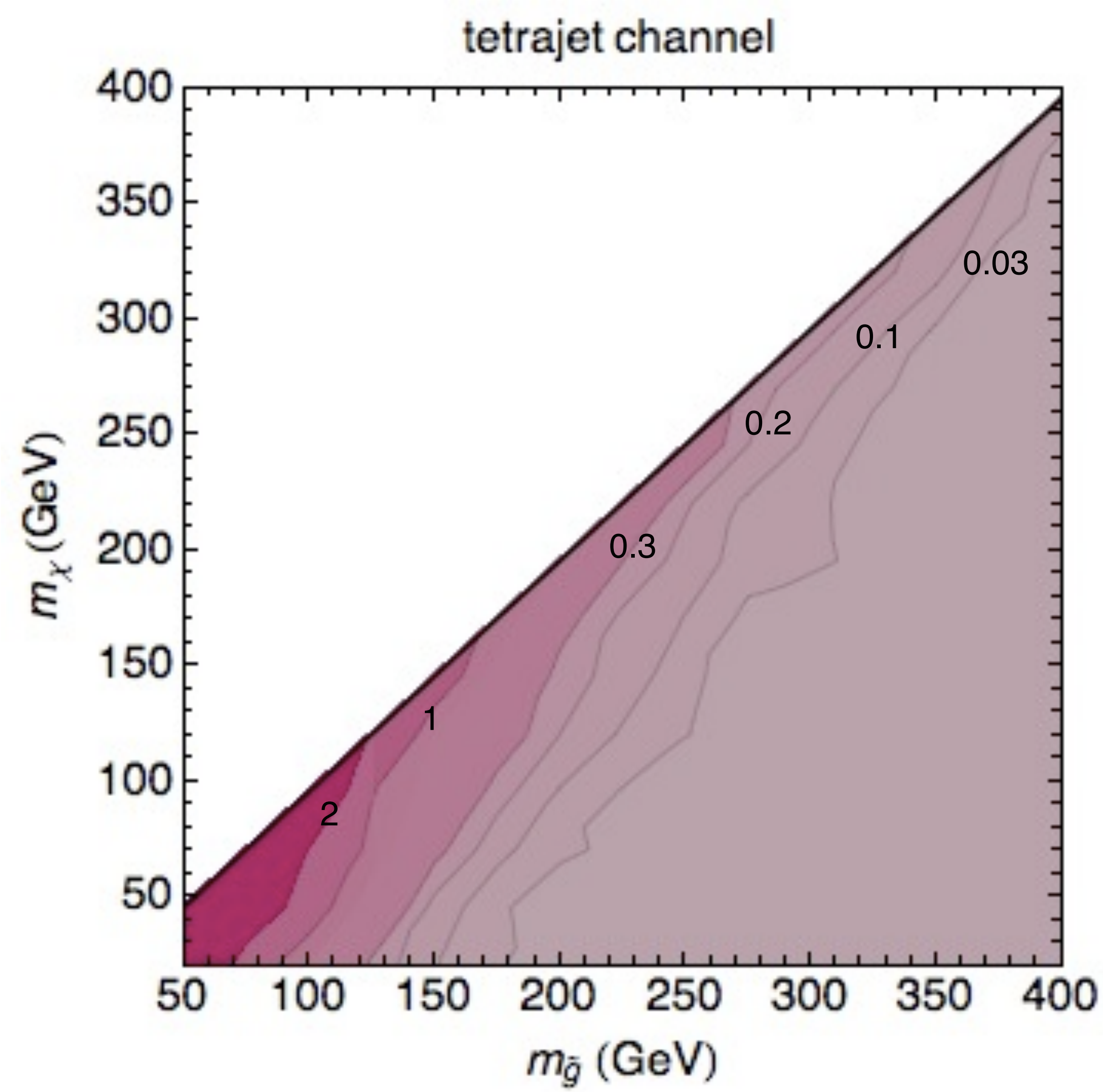


PS/ME Matching on Signal

Higher multiplicities affected more

Degenerate region can have limits altered by O(1)

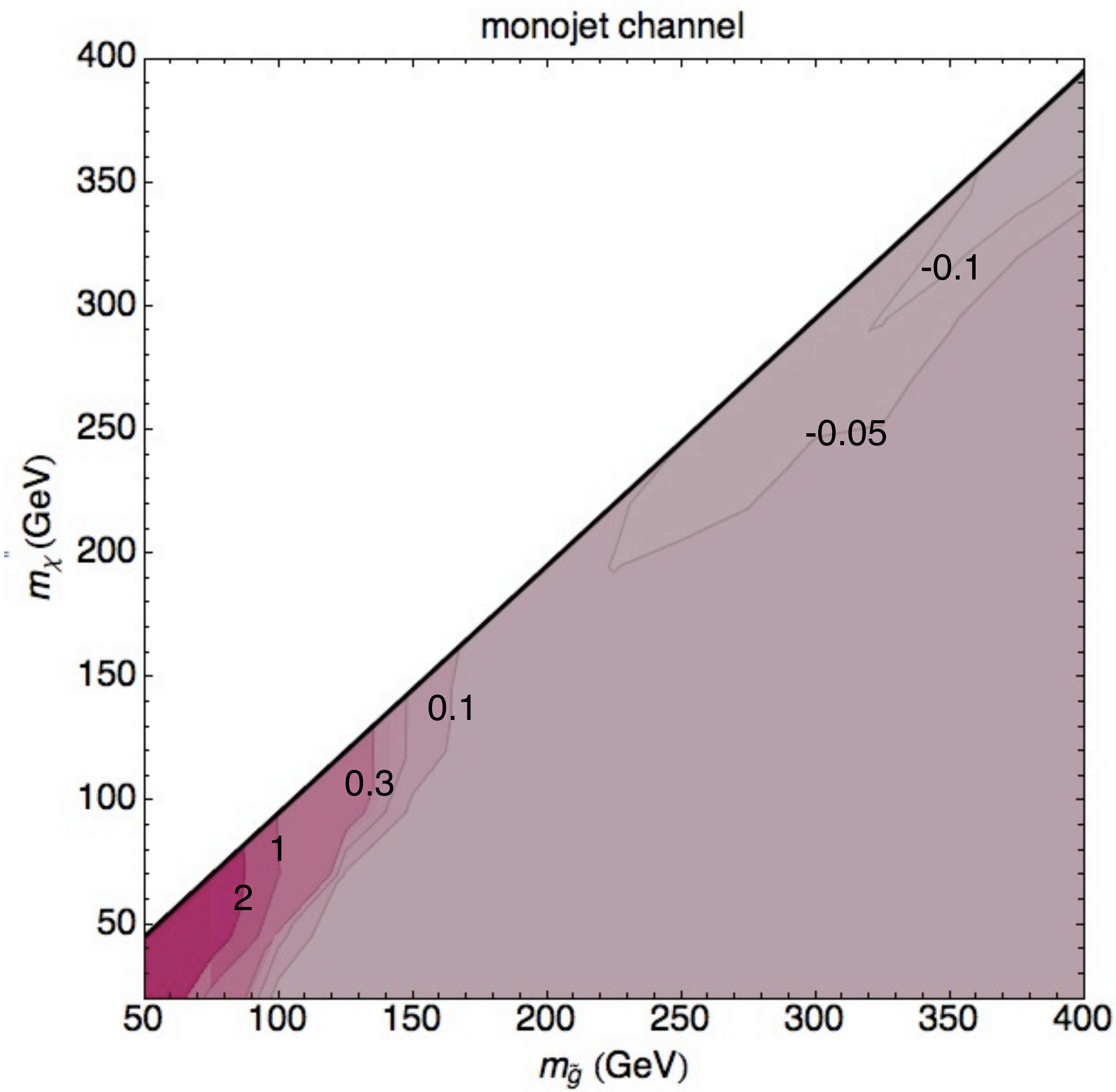




Generally increases sensitivity

$$\text{contours} = \frac{\sigma_{\text{lim}}^{\text{no-matching}}}{\sigma_{\text{lim}}^{\text{matching}}} - 1$$

Efficiencies are over estimated with jet vetos



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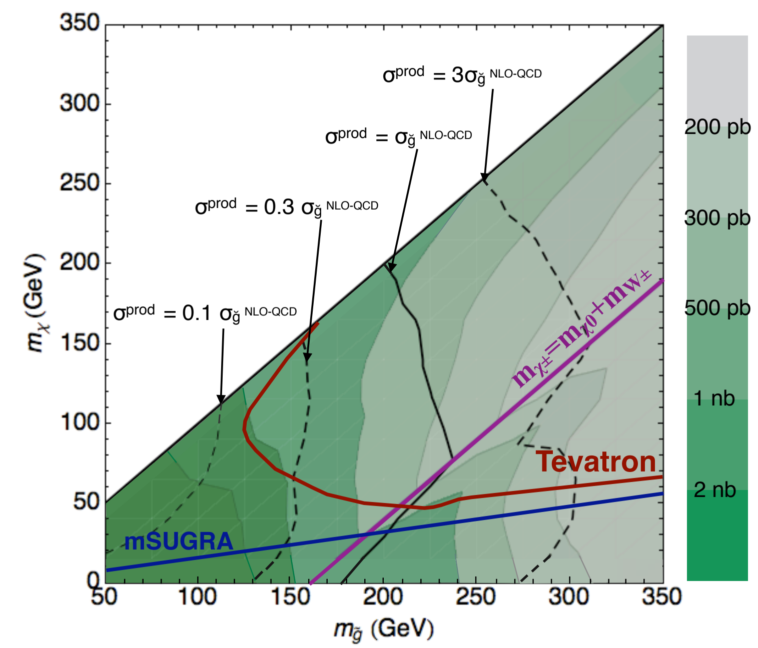
Looking towards future analyses

Current plans are for a single multijet search
Maximize reach for highest mass gluino discovery

Should maximize sensitivity to
smallest cross section for all masses
e.g. if only 10% of the decays are visible



Still need to be sensitive to light objects with
small cross sections/branching ratios

Cuts & Optimization

- Generated signal for a wide range of masses $m_{\tilde{g}}, m_{\tilde{\chi}}$ and the four decay modes discussed

- Estimated sensitivities for cuts on several kinematic variables,

$$\not{E}_T \;,\; H_T \;,\; p_{Ti} \;,\; M_{\text{eff}} \equiv \not{E}_T + \Sigma\, p_{Ti} \;,\; \frac{\not{E}_T}{M_{\text{eff}}} \;,\; \frac{p_{Ti}}{\not{E}_T}$$

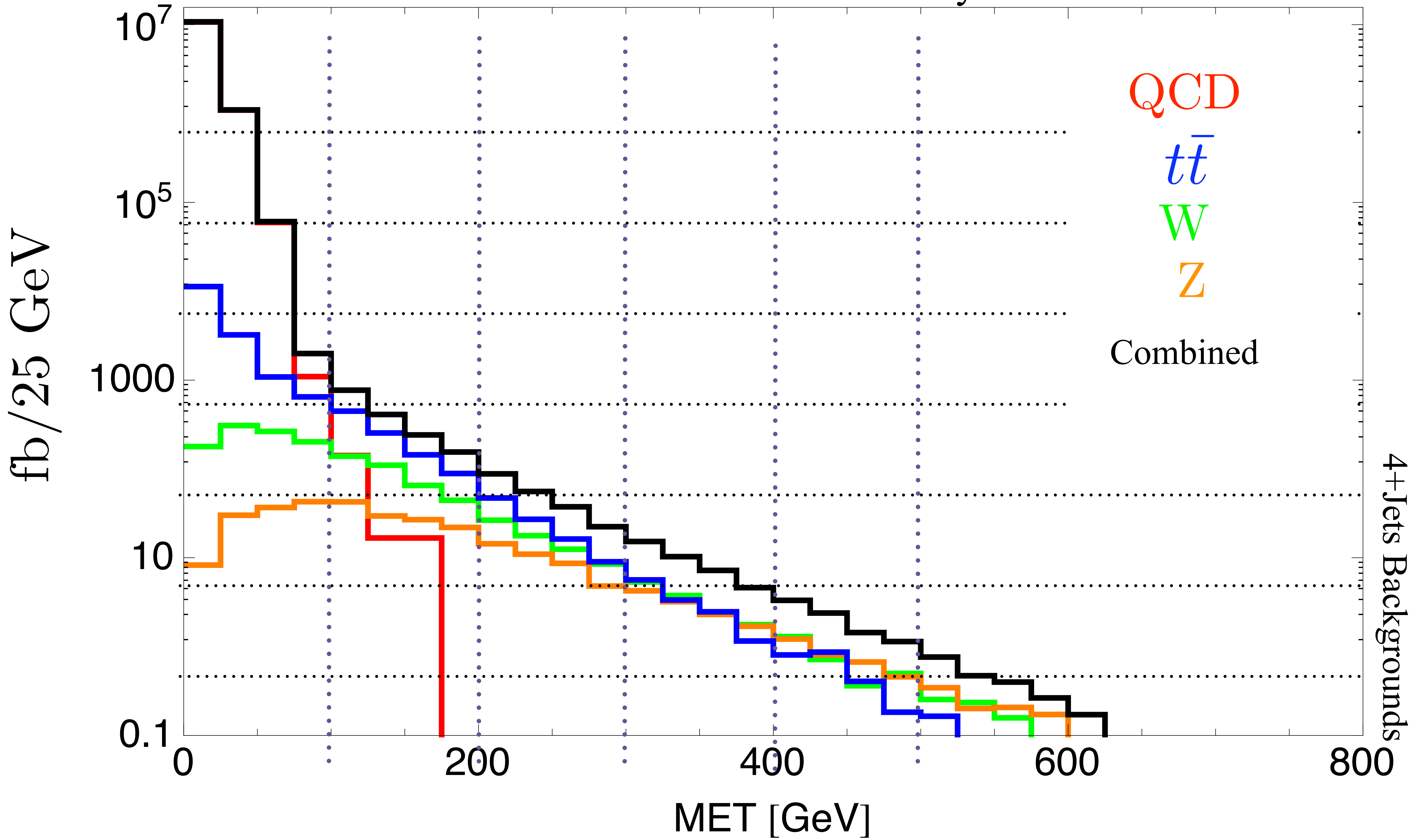
→ *Hard to beat missing and visible energy*

→ Stuck with combined cuts on $\not{E}_T$, H_T

7 TeV Backgrounds

Soon to be available at LHCBackgrounds.com

Match ATLAS MC Work Reasonably Well

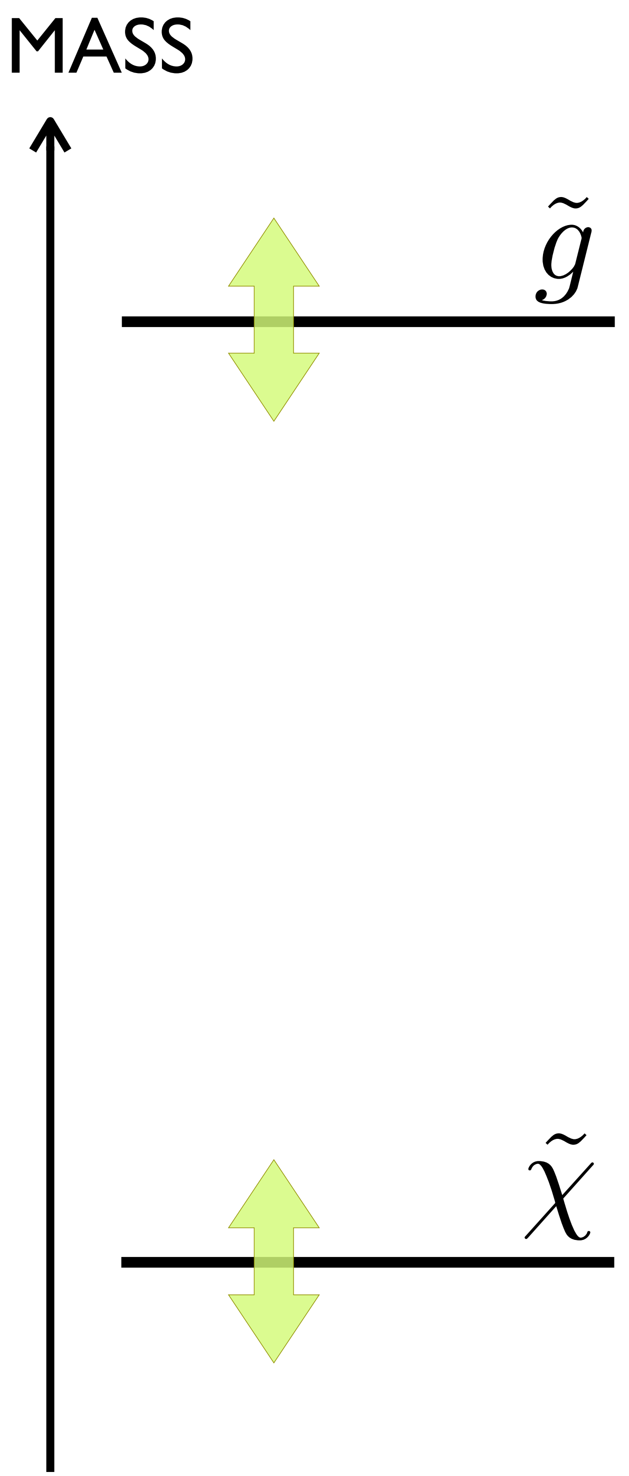


Include 30% systematic error on BG Estimates

Simplified Models

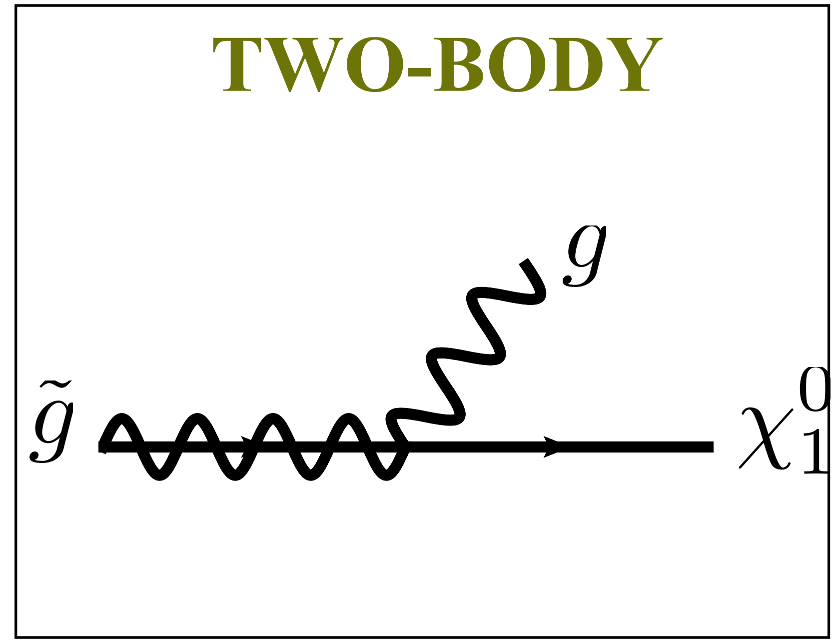
for this study

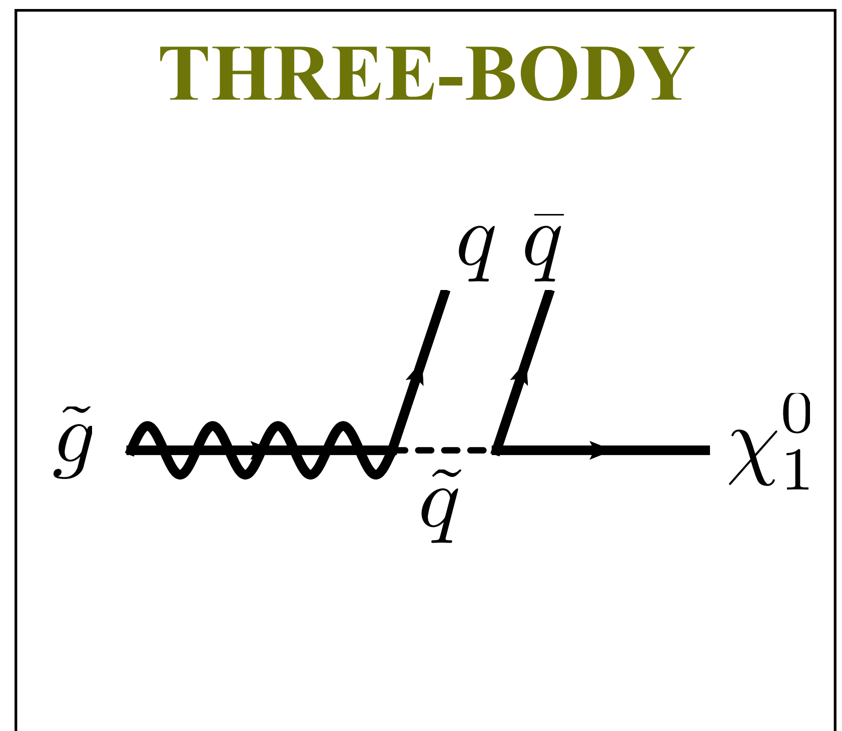
Direct Decays



color octet majorana fermion ("Gluino")

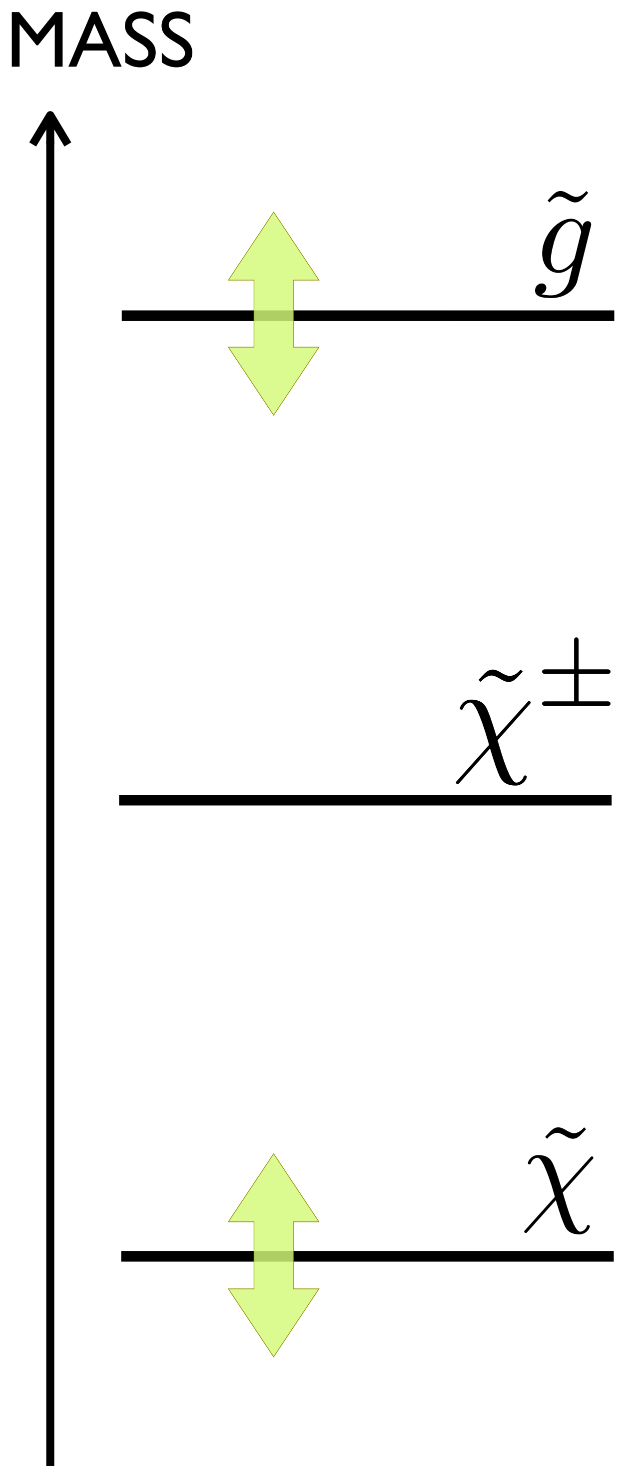
neutral majorana fermion ("LSP")





Simplified Models *for this study*

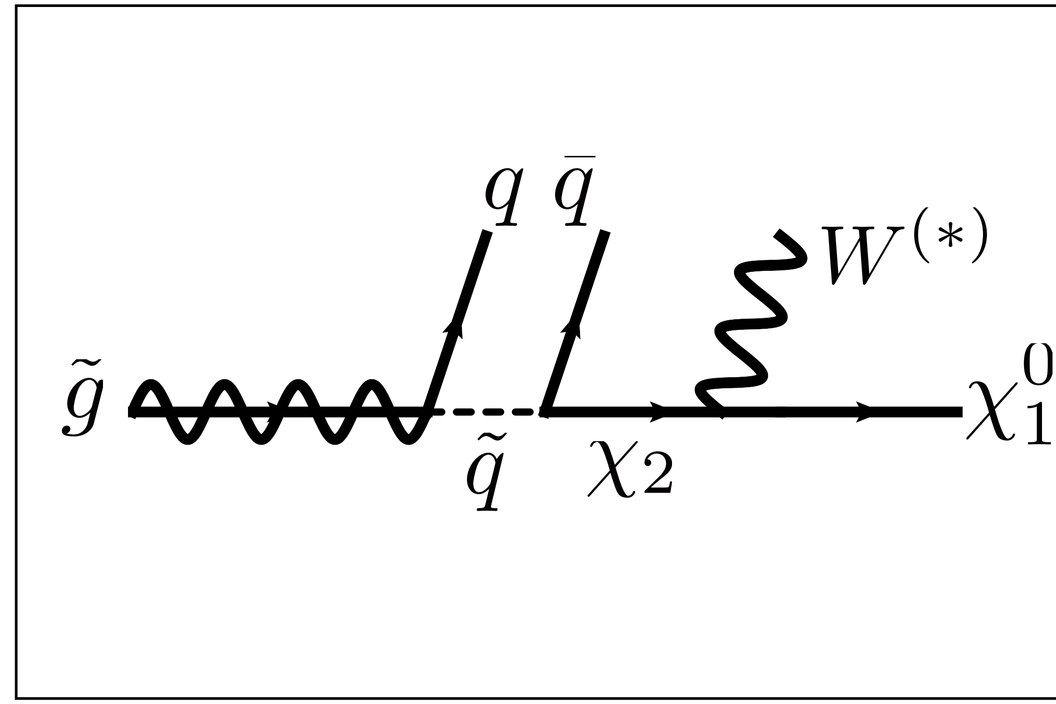
One-Step Cascade Decays



color octet majorana fermion ("Gluino")

electroweak majorana fermion ("Wino")

neutral majorana fermion ("LSP")

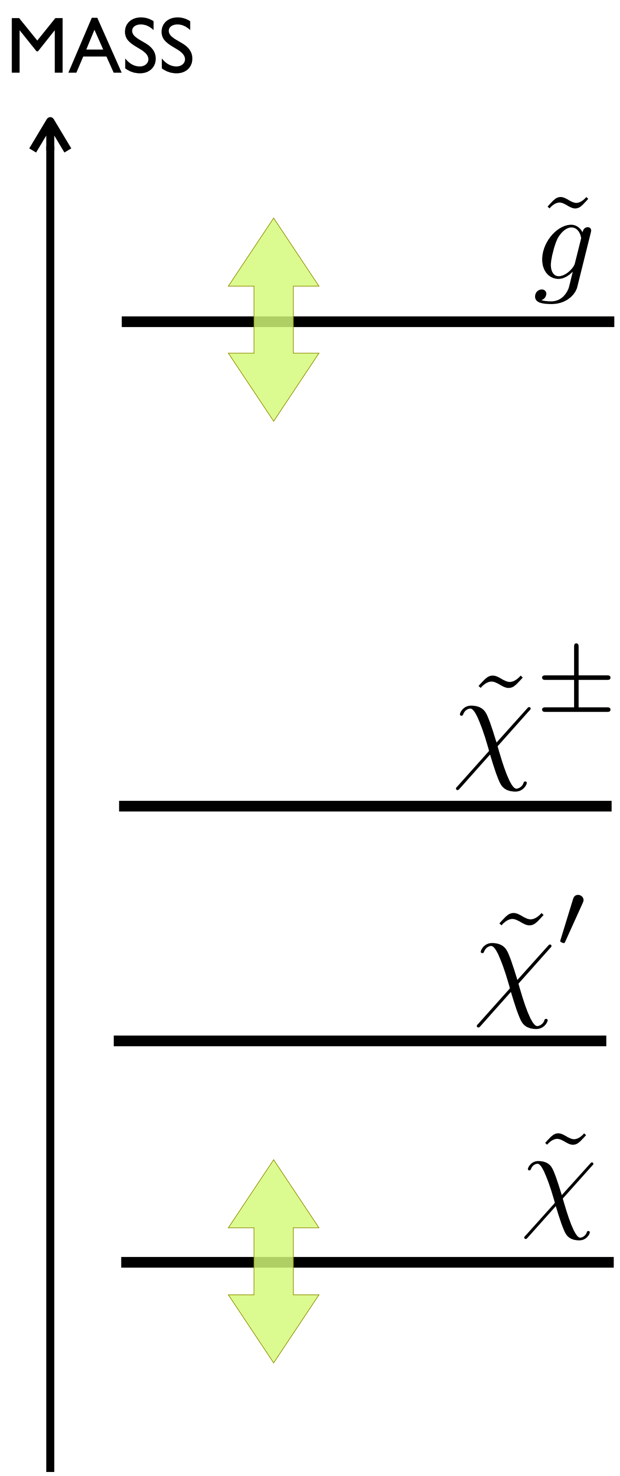


$$m_{\tilde{\chi}^{\pm}} = m_{\tilde{\chi}} + \frac{1}{2}(m_{\tilde{g}} - m_{\tilde{\chi}})$$

Simplified Models

for this study

Two-Step Cascade Decays

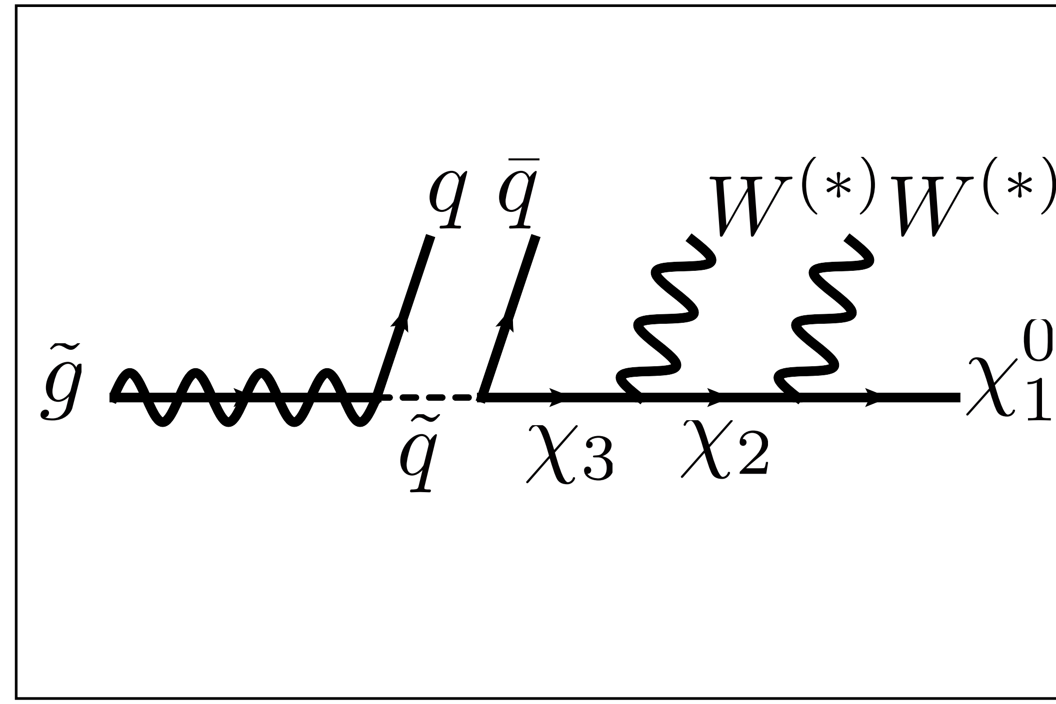


$\tilde{g}$ color octet majorana fermion ("Gluino")

$\tilde{\chi}^{\pm}$ electroweak majorana fermion ("Wino")

$\tilde{\chi}'$ neutral majorana fermion ("Higgsino")

$\tilde{\chi}$ neutral majorana fermion ("LSP")



$$m_{\tilde{\chi}^{\pm}} = m_{\tilde{\chi}} + \frac{1}{2}(m_{\tilde{g}} - m_{\tilde{\chi}})$$

$$m_{\tilde{\chi}'} = m_{\tilde{\chi}} + \frac{1}{2}(m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}})$$

Hunting for Optimal Cuts

Want to have good coverage
for all these models
for all kinematic ranges

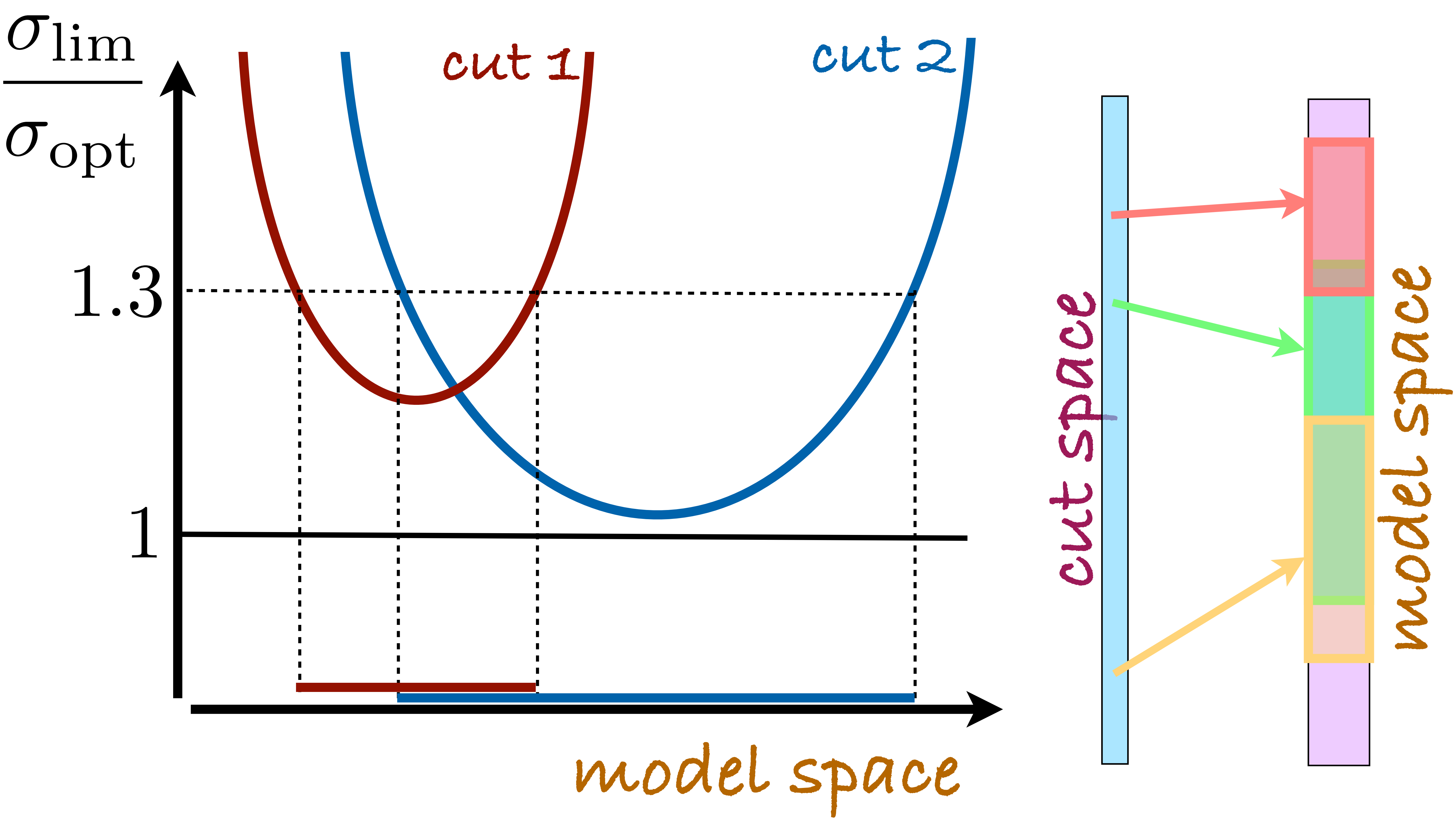
Want to minimize: $$\frac{\sigma_{\mathrm{lim}}(\mathrm{cut})}{\sigma_{\mathrm{optimal\ lim}}}$$

QUESTION: Is there a single cut whose sensitivity is close to optimal for all masses and decay modes?

ANSWER: No

Hunting for Optimal Cuts

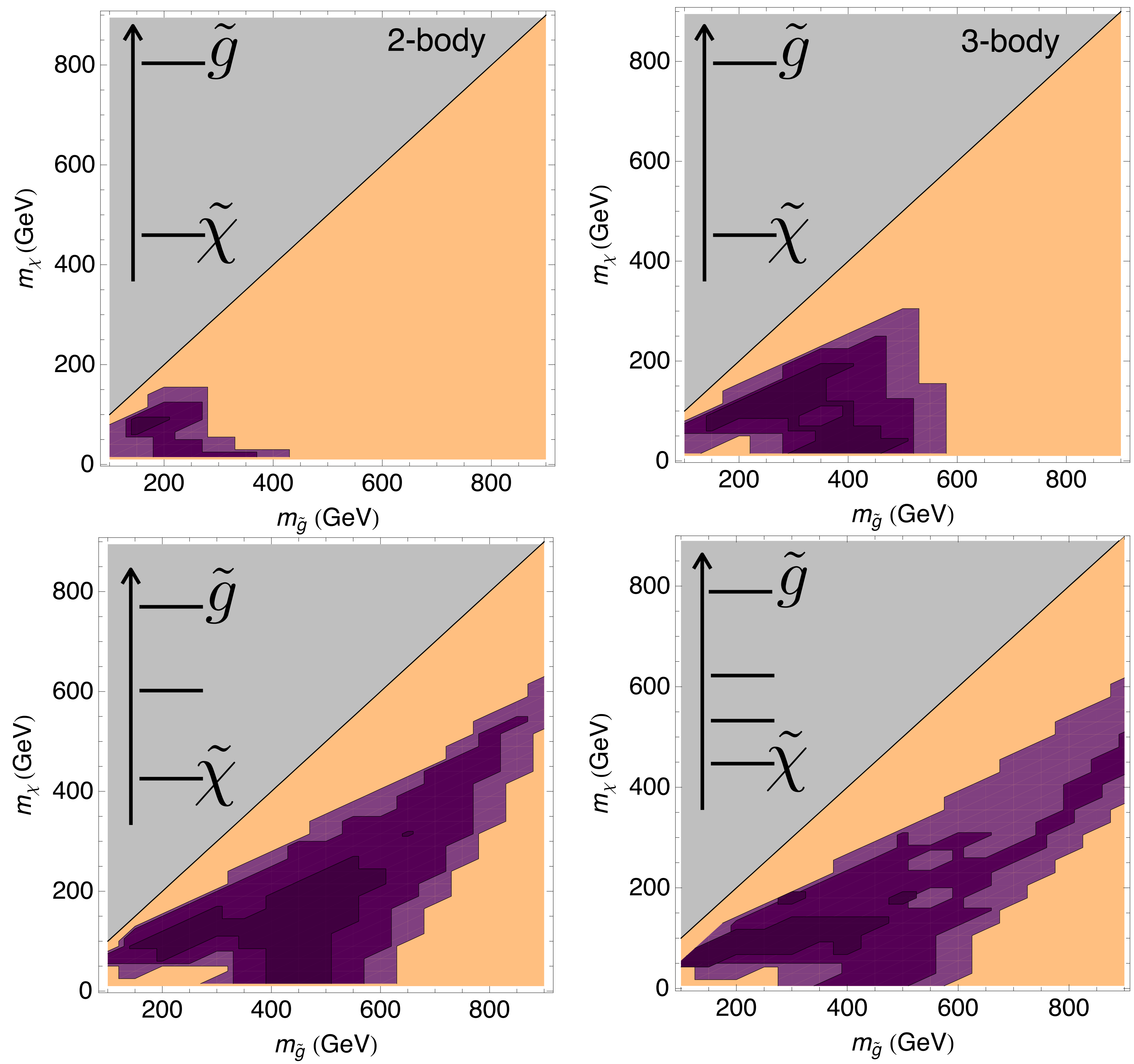
TASK: Find the *minimum* set of cuts on MET and H_T whose *combined* reach is close to optimal (within a given accuracy) for all models.



Hunting for Optimal Cuts

E.g.,
reach of the search region

$$\begin{cases} \not{E}_T \geq 150 \text{ GeV} \\ H_T \geq 750 \text{ GeV} \end{cases}$$



within 10% of optimal

within 20% of optimal

within 30% of optimal

Multiple Search Regions

- minimal set of cuts (*multiple search regions*) whose combined reach is within optimal to a given accuracy

  → for all masses and decay modes

  → for three luminosity scenarios: 10 pb^{-1}, 100 pb^{-1}, 1 fb^{-1}

- size of the set depends on the optimal accuracy

  ✦ 5% → $\mathcal{O}$(30 cuts)

  ✦ 10% → $\mathcal{O}$(16 cuts)

  ✦ 30% → $\mathcal{O}$(7 cuts)

  ✦ 50% → $\mathcal{O}$(4 cuts)

- not sensitive to exact values of the cuts
- only *comprehensive* when *combined*

Multiple Search Regions

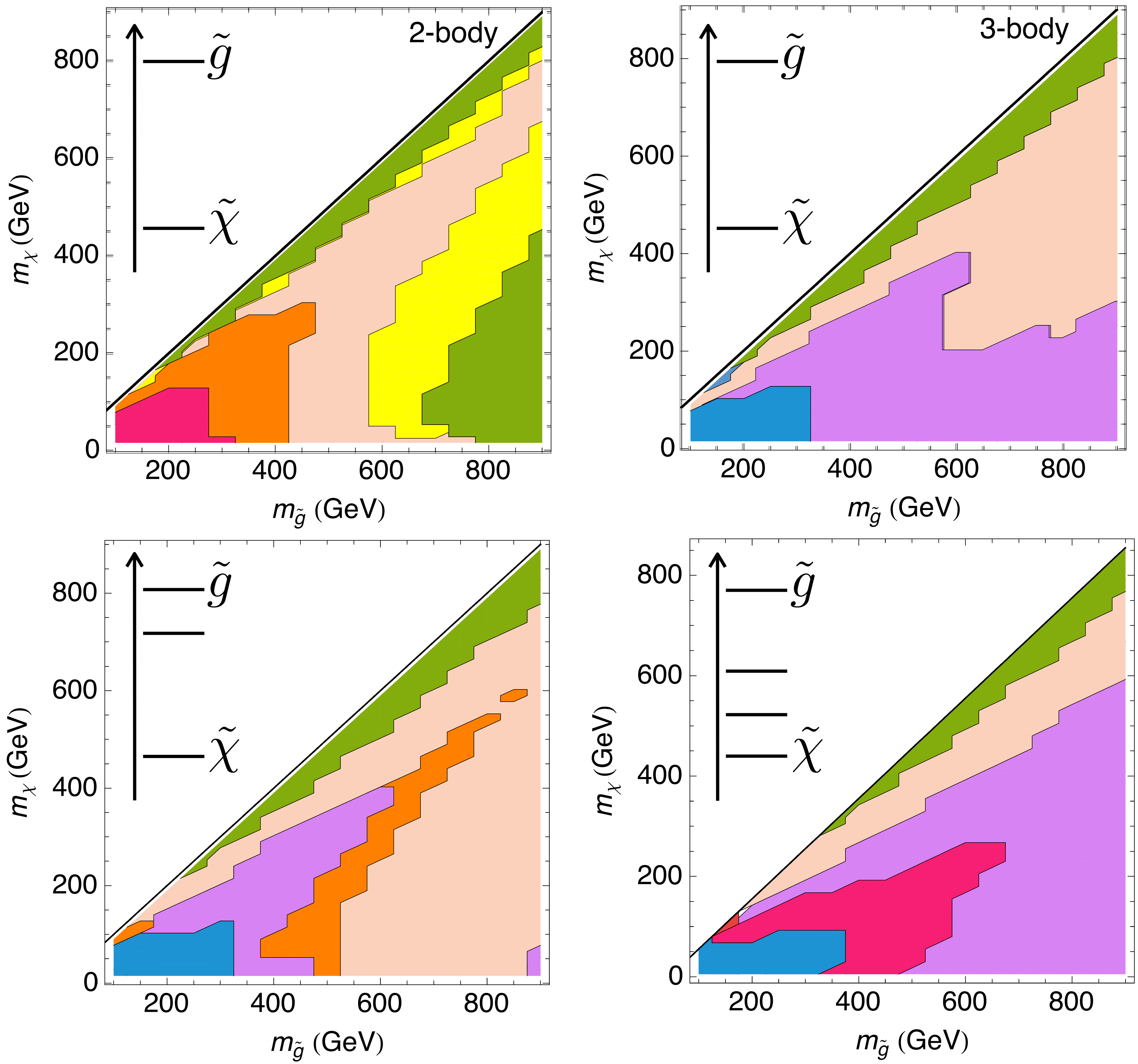
combined reach
within 30% of optimal

- 7 search regions necessary:

Dijet high MET	$\not{E}_T > 500$ GeV, $H_T > 750$ GeV
Trijet high MET	$\not{E}_T > 450$ GeV, $H_T > 500$ GeV
Multijet low MET	$\not{E}_T > 100$ GeV, $H_T > 450$ GeV
Multijet low MET + high H_T	$\not{E}_T > 100$ GeV, $H_T > 650$ GeV
Multijet very high H_T	$\not{E}_T > 150$ GeV, $H_T > 950$ GeV
Multijet moderate MET	$\not{E}_T > 250$ GeV, $H_T > 300$ GeV
Multijet high MET	$\not{E}_T > 350$ GeV, $H_T > 600$ GeV

Multiple Search Regions

combined reach
within 30% of optimal

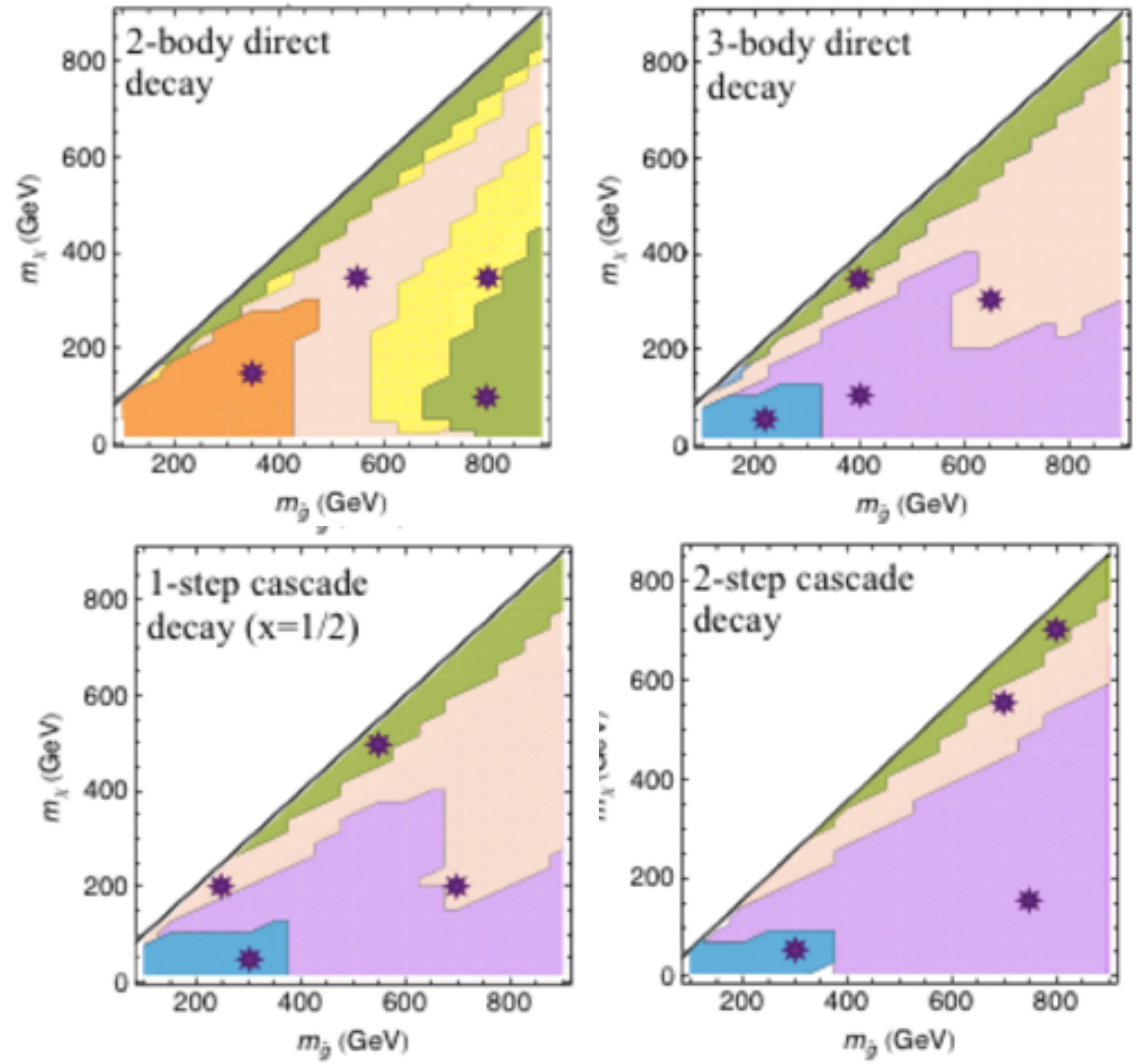


Multijet high MET

cut	ch	MET	H_T
	2+j	500	750
	3+j	450	500
	4+j	100	450
	4+j	100	650
	4+j	150	950
	4+j	250	300
	4+j	350	600

Designing Optimal Regions

- Choice of multiple search regions depends upon
  - backgrounds
  - detector efficiencies & acceptances
  - how good is good enough
  - etc
- Not something a theorist should be designing too closely
- Scans are expensive for experiments, providing benchmark theories saves effort
- We've done rough exploration of corners of parameter space looking for



List of Benchmark Models

- Chosen to maximize differences in how they appear in given searches
- Simple and easy to define
- Consistent theories on their own

Name	$m_{\tilde{g}}$ (GeV)	$m_{\tilde{\chi}^0}$ (GeV)	Decay
$\mathcal{M}_1$	800	100	direct 2-body
$\mathcal{M}_2$	800	350	direct 2-body
$\mathcal{M}_3$	550	300	direct 2-body
$\mathcal{M}_4$	350	150	direct 2-body
$\mathcal{M}_5$	250	50	direct 3-body
$\mathcal{M}_6$	400	100	direct 3-body
$\mathcal{M}_7$	400	350	direct 3-body
$\mathcal{M}_8$	650	300	direct 3-body
$\mathcal{M}_9$	150	50	1-step cascade (x=1/4)
$\mathcal{M}_{10}$	400	80	1-step cascade (x=1/4)
$\mathcal{M}_{11}$	450	350	1-step cascade (x=1/4)
$\mathcal{M}_{12}$	600	200	1-step cascade (x=1/4)
$\mathcal{M}_{13}$	250	200	1-step cascade (x=1/2)
$\mathcal{M}_{14}$	300	50	1-step cascade (x=1/2)
$\mathcal{M}_{15}$	550	500	1-step cascade (x=1/2)
$\mathcal{M}_{16}$	700	200	1-step cascade (x=1/2)
$\mathcal{M}_{17}$	250	0	1-step cascade (x=3/4)
$\mathcal{M}_{18}$	350	200	1-step cascade (x=3/4)
$\mathcal{M}_{19}$	450	100	1-step cascade (x=3/4)
$\mathcal{M}_{20}$	900	400	1-step cascade (x=3/4)
$\mathcal{M}_{21}$	300	50	2-step cascade
$\mathcal{M}_{22}$	750	150	2-step cascade
$\mathcal{M}_{23}$	750	550	2-step cascade
$\mathcal{M}_{24}$	800	750	2-step cascade

$$m_{\chi^\pm} = m_{\chi^0} + x(m_{\tilde{g}} - m_{\chi^0})$$

Lots more to be done

- This work focused on pair produced colored octets

- Important to look at other possibilities:

  → resonant production

  → color triplets (radiate less - different search regions for compressed spectra?)

  → monojet signatures not from radiation (*e.g.*, squark-neutralino associate production, resonantly produced composite gluon to gluon + invisible)

  → multijet signatures with no missing energy (very different story)

  → other channels (leptons, heavy flavor, photons)

- Joint effort in this direction: http://lhcnewphysics.org

Summary

- Searches for new colored states with jets+MET signatures are promising with the LHC data of next year

- Benchmark driven searches are suboptimal (and too model dependent)

- Reach can be highly improved by:

→ less model dependent parametrizations (simplified models)

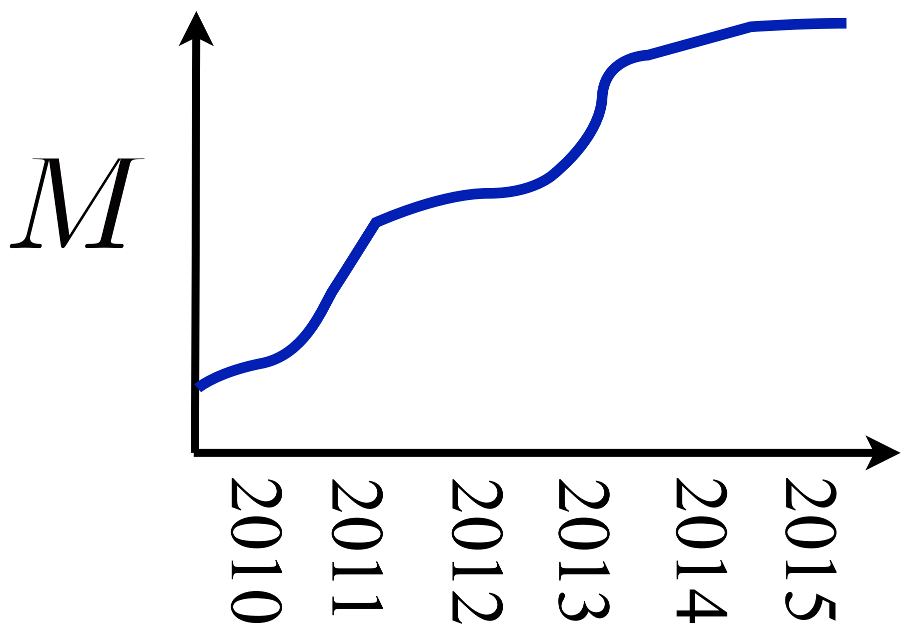
advantage: sensitive to a large range of phase space

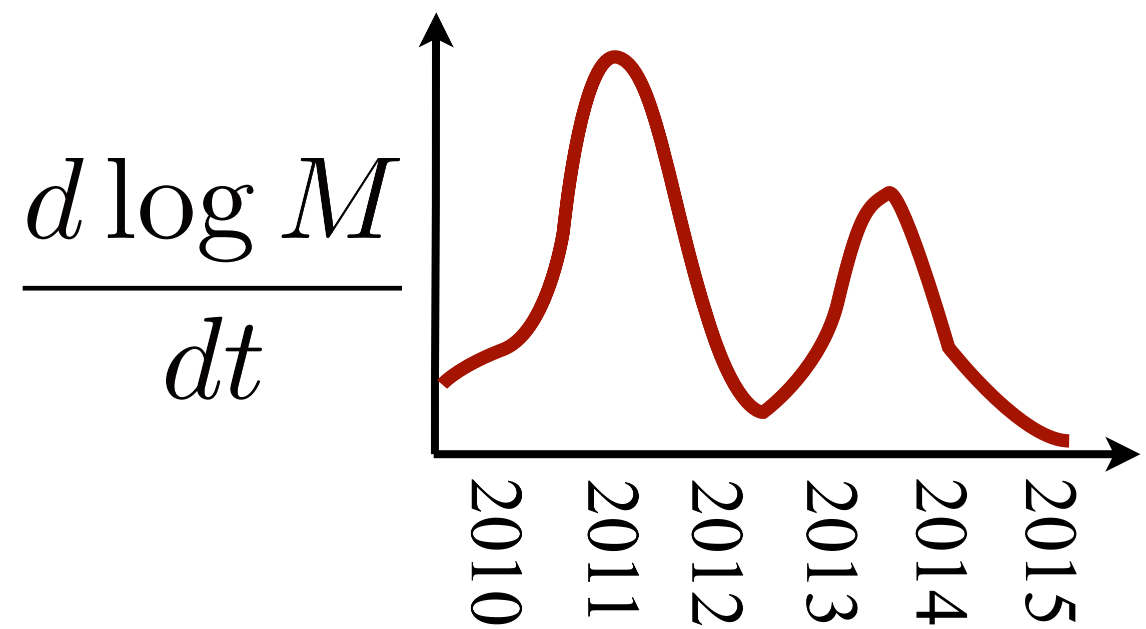
→ multiple search region strategy

advantage: combined reach is very close to optimal in the whole parameter space of models

2011 is the year for discoveries

Mass Reach as function of time





Lots of work to be done

http://LHCNewPhysics.org

End.